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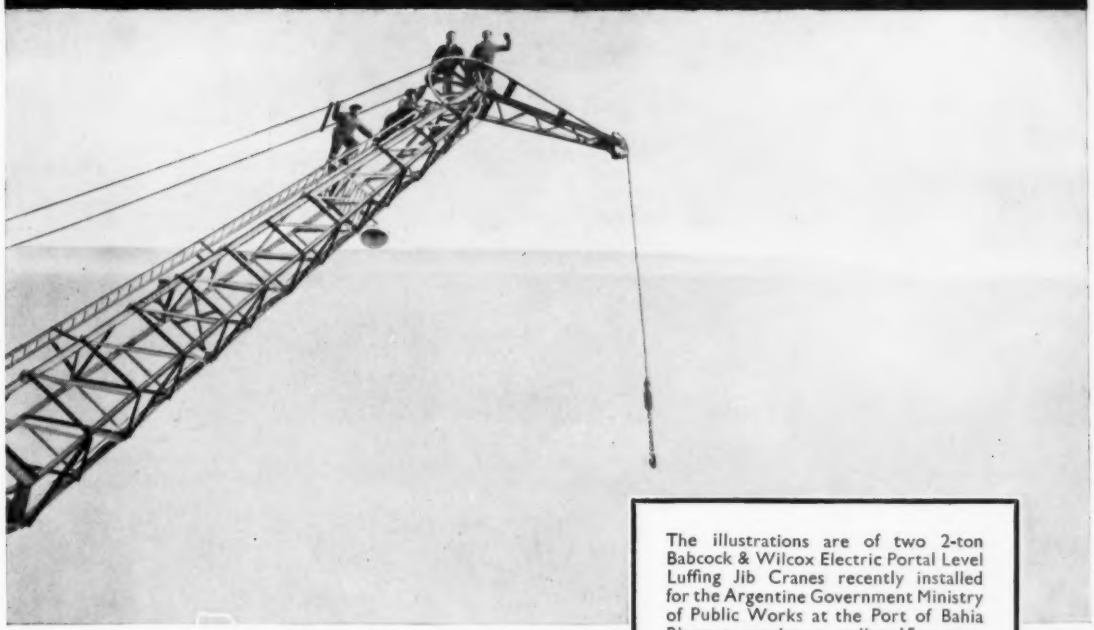

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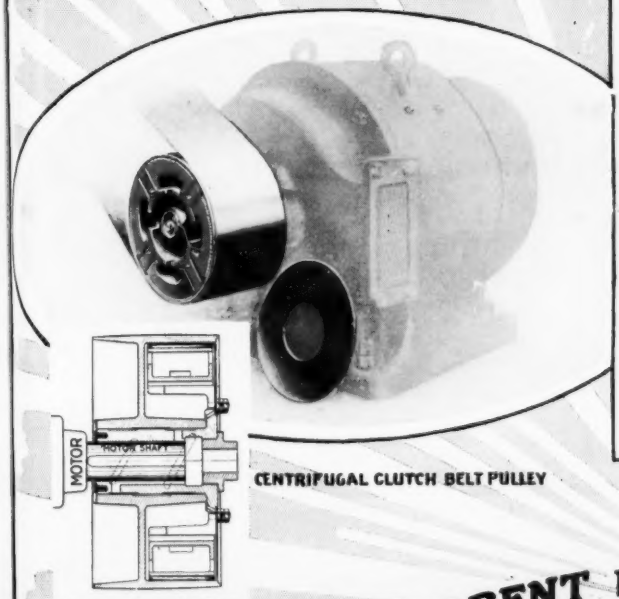

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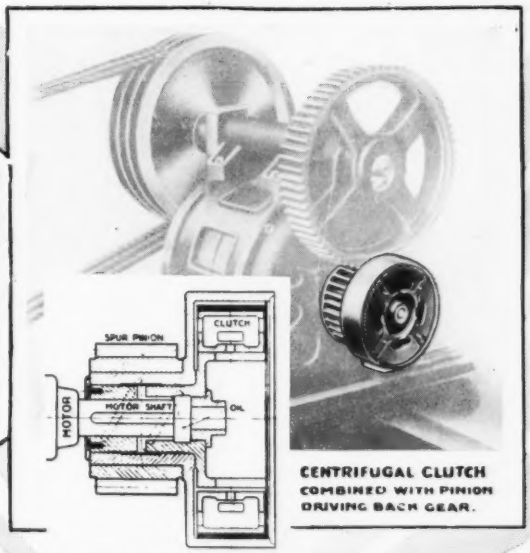

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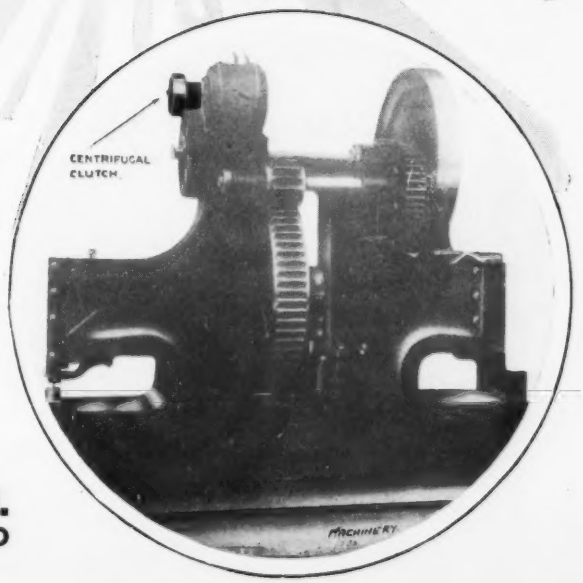

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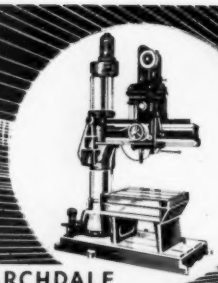

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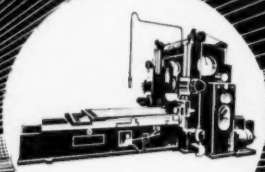

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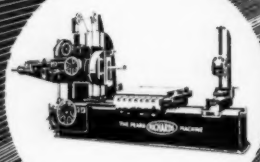

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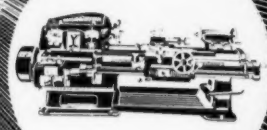

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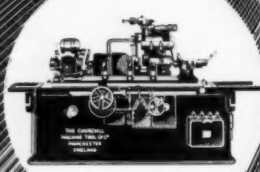

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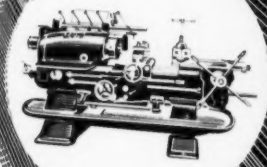

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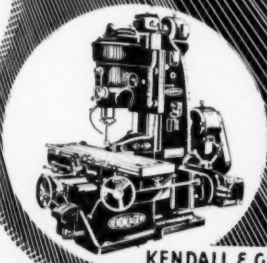

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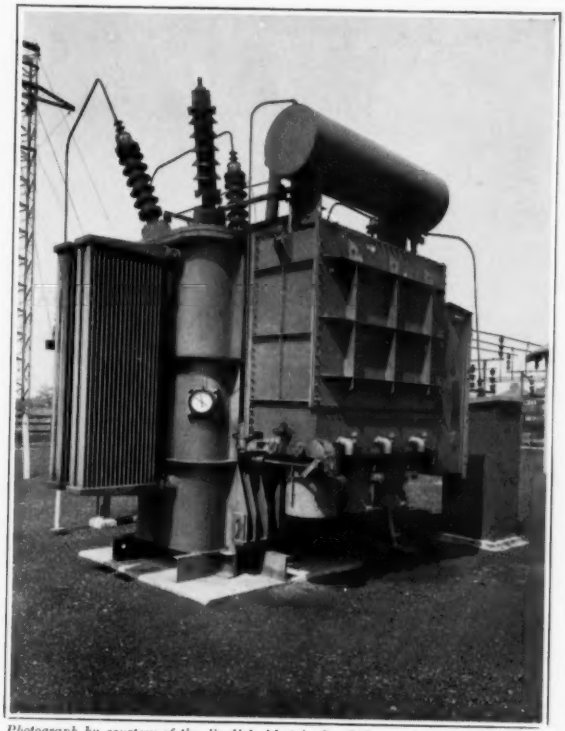

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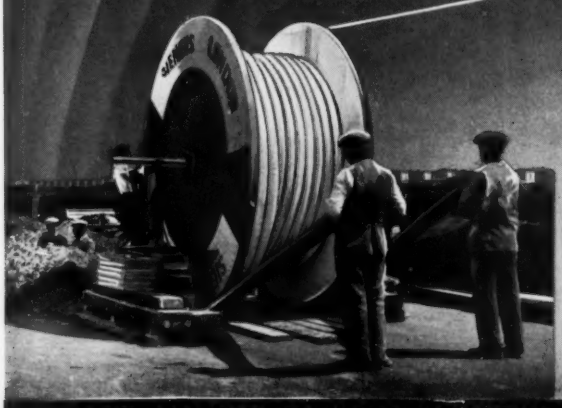

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CONTENTS.

PAGE

NEW DEVELOPMENTS IN AIR-BREAK CIRCUIT-BREAKERS – 5

ELECTRICAL PLANT FOR TESTING INTERNAL COMBUSTION ENGINES – – – – 20

SOME NOTES ON FUEL INJECTION AND COMBUSTION IN COMPRESSION IGNITION ENGINES 25

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EDITORIAL.

With the ever-increasing necessity for reducing the risk of fire, which is always present to some degree with oil-immersed switchgear, attention has been focused recently on the air-break switch. In the first article in this issue, Mr. A. R. Blandford describes some new and important developments in air-break circuit-breakers made by the Company. In the introduction the Author points out that whilst air-break circuit-breakers have been used on low-voltage circuits from the early days of D.C. practice, with the advent of A.C. at higher voltages the oil circuit-breaker was developed and adopted almost to the exclusion of the air-break type.

Now that consideration is once again being given to the air-break circuit-breaker, present-day testing methods have revealed that changes in its design are required, if

it is to possess all the good points of the oil circuit-breaker.

In the article, new designs of low-voltage and high-voltage air-break circuit-breakers developed by the Company are described. These incorporate new forms of arcing chambers. The use of refractory metal in place of carbon, and laminated brush-type contacts being replaced by silver-faced solid copper contacts are other novel features.

The application of the design principles of the arcing chamber developed for 750-volt maximum service has made it possible to produce a circuit-breaker for 3,300-volt service. The problem of completely enclosing air-break circuit-breakers and obtaining excellent interruption in an enclosure of small dimensions has been solved in the air-break circuit-breakers under review.

In the second article Mr. W. E. Streete discusses the use of electrical machines for obtaining reliable data on the performance of internal combustion engines. Although the water brake has been hitherto largely used for this purpose, the electrical dynamometer has a number of advantages which are perhaps not generally appreciated. Whilst with the hydraulic dynamometer the mechanical energy from the engine is dissipated in the form of heat and is thus lost, the electrical energy obtained from an electric dynamometer can be used to supplement the factory supply, either direct or through suitable converting plant, thus enabling some of the generating plant in the factory power station to be shut down with a saving in power cost. Moreover, the electric dynamometer can also be used as a motor for starting the engine or for running-in purposes.

In the concluding article of this issue, Mr. G. H. Paulin reviews some of the problems and general principles involved in the injection and burning of the fuel in compression-ignition engines.

The Author points out that with the modern airless injection engine the design of the fuel injection system is of paramount importance to the economy and reliability of the oil engine as a prime mover.

The combustion of the fuel, wave action in fuel pipes, and the distribution of the fuel mist in the air charge in the cylinder are some of the problems dealt with in the article, which is accompanied by a number of interesting indicator and other diagrams.

New Developments in Air-Break Circuit-Breakers.

By A. R. BLANDFORD, Chief Engineer and Manager Switchgear Department.

Introduction.

Air-break circuit-breakers have been in use on low-voltage circuits in the electric power industry from the early days of D.C. practice. In this service such breakers have maintained satisfactory performance with but few failures and at a low maintenance cost. With the application of alternating currents at higher voltages, the oil circuit-breaker was introduced, and the reason for the development of this type of switchgear for low-voltage circuits is somewhat obscure, particularly in view of the satisfactory performance of the air-break gear.

With present-day testing methods, the air-break circuit-breaker, as also the oil circuit-breaker, has necessitated the attention of the designer in order to improve its interrupting capacity, and to ensure that none of the desirable features of the oil circuit-breaker has been sacrificed in the development of the air-break circuit-breaker. It is now generally recognised that the oil circuit-breaker, as an interrupting unit, is an approved and tested piece of apparatus, but that it will always incorporate the risk of fire.

The production of an air-break circuit-breaker possessing all the good points of the oil-break gear, besides dispensing with oil, is a desirable advance in the march of progress.

It should be remembered that 25 MVA is a small amount of power as a value of rupturing capacity, but this value, which is a standard at 400 volts, produces approximately 36,000 R.M.S. amperes breaking current, which demands a peak-making current of 92,000 amperes. In dealing with currents of this magnitude, which by comparison are five times greater than met with at 1,500,000 kVA. rupturing capacity at 132 kV., it was found on short-circuit test that contact deterioration in oil was so severe when carrying out a B.S.S. duty-cycle, and this with refractory metals used for the arcing contacts, that attention needed to be turned to some other form of arc-rupturing device for capacities above 15 MVA. at 400 volts.

The cause of the excessive burning of contacts in oil at currents of the order under consideration is due to the constriction of the arc by the oil which localises the arc, forming undesirable craters. The cure obviously demanded a method which permitted free movement of the arc and at the same time provided the necessary amount of constriction to prevent it from getting out of control. As in the oil circuit-breaker, the localisation of the arc is due to the inertia of liquid; attention was therefore directed towards the air-break circuit-breaker, which, at voltages up to 3,300 D.C., had given such very satisfactory service.

As already mentioned above, the air-break circuit-breaker is not a new or novel means of circuit interruption; but it became apparent on test that the older types of air-break circuit-breakers needed considerable development to make them suitable for modern operating and test conditions. Improvements were needed to make the equipment suitable for :—

(*a*) Complete metal enclosure.
(*b*) Making and breaking the heavy short-circuit currents on the contacts.
(*c*) Standing up to the heavy magnetic forces.
(*d*) Mounting in the same space as that required for oil circuit-breakers.

In addition, consideration has been given to simplicity of design, breaking capacity, high insulation level and high operating speed. Each of these objectives has been achieved to the highest degree in both types of " English Electric " circuit-breaker described in this article.

400-VOLT AIR-BREAK CIRCUIT-BREAKER.

Design of Arcing Chamber.

The usual method of controlling an arc in air is by means of magnetic blow-outs which, in themselves, generally tend to intensify the noise of the circuit-breaker during operation and very frequently they introduce complications with regard to thermal capacity and the satisfactory insulation of the blow-out winding from the arc and the earthed magnetic paths from the arc.

In the design of the arcing chamber for this voltage there are a number of insulating plates of non-gas-forming material with V-shaped slots—see Fig. 1a*. They are spaced at intervals of approximately $\frac{3}{16}$ in., and at right angles to the arc. This allows free ventilating space at the top for escape of the gases, thus keeping down back-pressure, which would prevent the gas from rising freely. It will be noticed the slots are much narrower at the upper end than at the lower end where space is required for the movement of the arc tips and the contact arm.

An efficient interrupting chamber requires in its design a correct balance of arc constriction and magnetic control. The shape of the insulating plates and the spacing ensure sufficient constriction and reduce the arc section sufficiently to make the magnetic operation most effective.

* In the arcing chamber illustrated, a number of the magnetic plates have been removed in order to expose the insulated plates. The shape of the magnetic plates will be seen from the plate which has been placed above the chute.

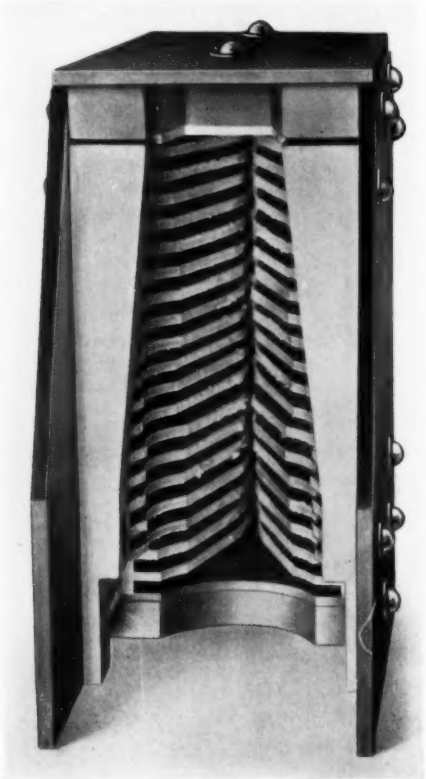


Fig. 1a.—Arcing Chamber—Bottom view, showing arrangement of Insulating Plates.

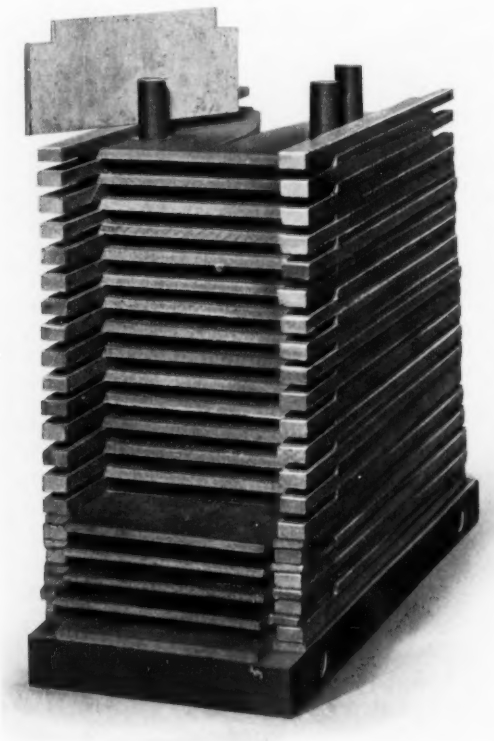


Fig. 1b.—Arcing Chamber—Top view, showing location of Iron Plates.

Magnetic control is obtained by self-induction, by mounting a series of iron plates equal in number and having the same spacing as the insulating plates. They are mounted in the same plane and situated at the top of the arcing chamber as shown in Fig. 1b, and in this manner they offer no additional restriction to the arc or the arc gases. The iron plates also have the effect of more efficiently cooling the gases which have previously been acted upon by the insulating plates; thus there is very little visible display of gases at the top of an arc-control device constructed in this manner.

It has been found that a chamber built in this way is almost equally suitable for D.C. interruption, as the field in this case is strongest when the current is high at the beginning of interruption. This allows the effect produced by the magnetic control of the field to be initially high to counter the ionising action produced by the heavy current, and likewise as the current decreases, both ionisation and the magnetic control de-ionisation forces subside. During A.C. operation the arc is interrupted at an early current zero, but the arc drop is not high until the end of the arcing half-cycle, owing to the current sine wave and its effect on the field. There is normally only one half-cycle of arcing except in cases where the contacts part just prior to current zero, when the time would be one half-cycle longer.

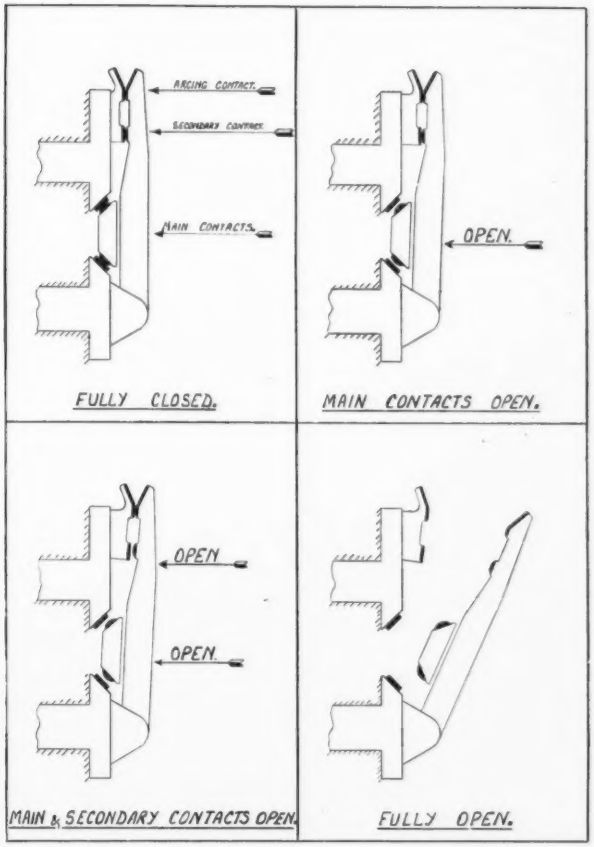


Fig. 2.—Contact opening sequence of 400-volt Air-break Circuit-breaker.

Breakers equipped with these interrupters have been tested with satisfactory interruption up to maximum short-circuit capacity in earthed enclosures having the top surface only 1 in. above the arc chamber. The chamber is also effective as a silencer and considerably reduces noise. Voltage drop in the chamber is approximately 50 volts R.M.S. A.C. per inch of arc length when clearing on a 400-volt 3-phase circuit.

Construction.

Air-break circuit-breakers in this category have to deal with large values of current, and one of the first considerations in the design of such a breaker is to ensure that the normal current-carrying section of the breaker is unaffected by short-circuit interruption. In the Company's breaker this has been achieved in a particularly satisfactory manner by resorting to what may be termed "three-stage" contact arrangement. Fig. 2 illustrates the contact opening sequence: The first stage, consisting of main contacts, serves only to carry the load; the second is an auxiliary arcing contact stage, which serves to protect the main contacts from deterioration during interruption and, at the same time, reduces the time interval during which the main arcing contacts have to deal with the whole of the current, either during a "making" or a "breaking" movement; and the

Fig. 3a.—Circuit-breaker Contact construction — open position.

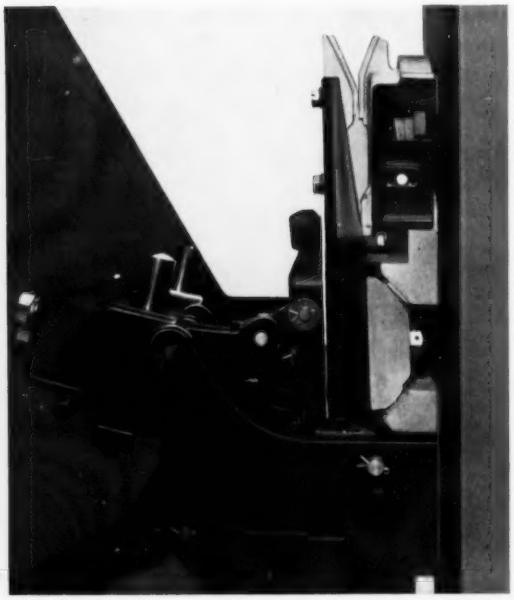


Fig. 3b.—Circuit-breaker Contact construction — closed position.

third stage, of course, consists of the final arcing contacts.

In order to provide for the correct mechanical sequence of operation of the contacts, a rigid, pivoted contact arm, carrying a floating main-contact bridging member, and rigidly fixed secondary contacts, comprise the moving contact system. A movable platform member is attached to the panel and is connected to the upper main fixed contact of the first stage on the panel. As the breaker opens the former moves, conjointly with the contact-carrying arm, in such a way that the secondary contacts of the second stage and the arcing contacts of the third stage do not slide on each other or separate. The necessary freedom of movement for the sliding platform member is provided by a slot in the sideplates which support it. After a sufficient degree of motion has taken place to enable the main contacts to separate, a pin, which is a part of the platform member, reaches the end of the slot in the sideplates, whereupon the secondary contacts part. With continued further action the platform member pivots about this pin and the secondary contacts on the stationary side move backwards, while the arcing contacts remain closed until the stop at the upper portion of the platform member reaches its limit position ; at this point the arcing contacts separate.

By means of this construction it has been possible to enclose the springs and shunts completely and to provide a simple design, unusually neat in appearance, which, at the same time, obviates the undesirable features of the earlier types of air-break circuit-breaker in which the moving contact and the arcing contact are usually of flexible construction, and therefore affected by the magnetic blow-off forces which arise with the passage of short-circuit currents.

This arrangement of the contact system is so effective that the overall dimensions of the new breaker for 1,600 amperes are no greater than those of the earlier forms of simple breaker which incorporated a laminated brush construction, and were rated at only 800 amperes for the same temperature rise.

The lower and fixed main contact block of the first stage is constructed of copper and is pro-

vided with a flat copper bridging member which breaks contact when the circuit-breaker is opened. In order to increase the current-carrying capacity of these contacts, silver plates are brazed on to the contact faces of both the moving and stationary members. These plates are of an adequate thickness of material, in order to ensure long life and freedom from maintenance. The bridging-contact member is held in the closed position in contact with its fixed members by powerful spring pressure, which is sufficient to ensure a low contact voltage drop with normal load current.

No attempt is made in the arrangement of the contact surfaces to ensure more than a high-pressure silver line-contact, since this is superior to silver-faced butt contacts of low pressure.

As is shown in Figs. 3a and 3b, the shape of the surface of the silver plates of the bridging member is segmental in order to ensure the correct alignment between them and the main contacts, which are fixed at an angle of 45 deg., so that the contact lines will come to lie on the surface of a cylinder. Thus, correct alignment of the contacts is achieved, since the cylinder will align itself with the two planes formed by the stationary stub contact members, if the bridging member is free to slide to the correct position.

The material for the secondary contacts must be suitable for resisting a certain amount of arcing ; and, since the chief object of these contacts is to protect the main contacts from burning, the contact drop of this material must be kept as low as possible. The material for the arcing contacts must resist damage from the arc ; and as the question of contact drop is not so important with these, the material used for this purpose is different from that used for the secondary arcing contacts. In both cases the material is of metal, and is greatly superior to carbon, since the contact volume can be made very much smaller, and can have a better thermal capacity as well as

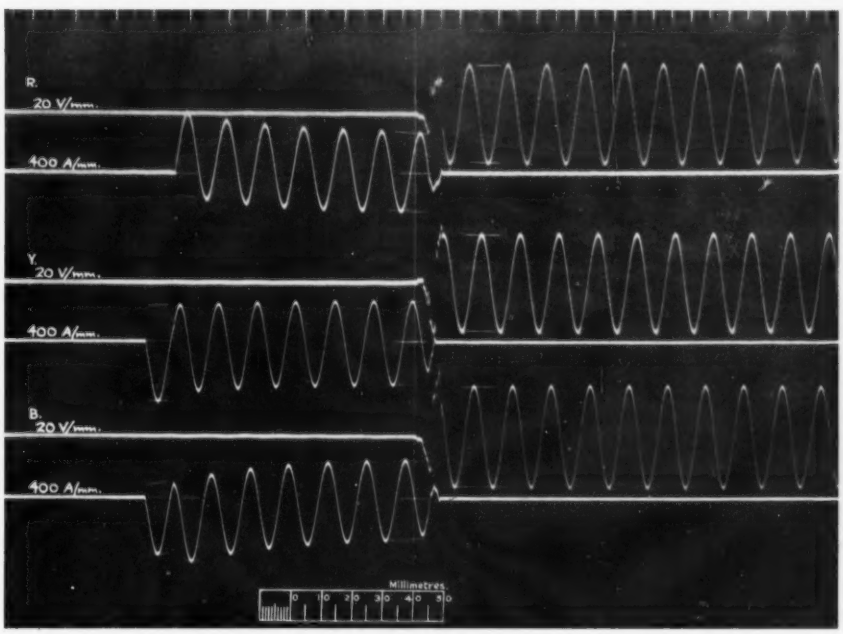


Fig. 4.—Oscillogram of 10% 3-phase "break shot," symmetrical amps 3680, 400 volts, 2.5 MVA.

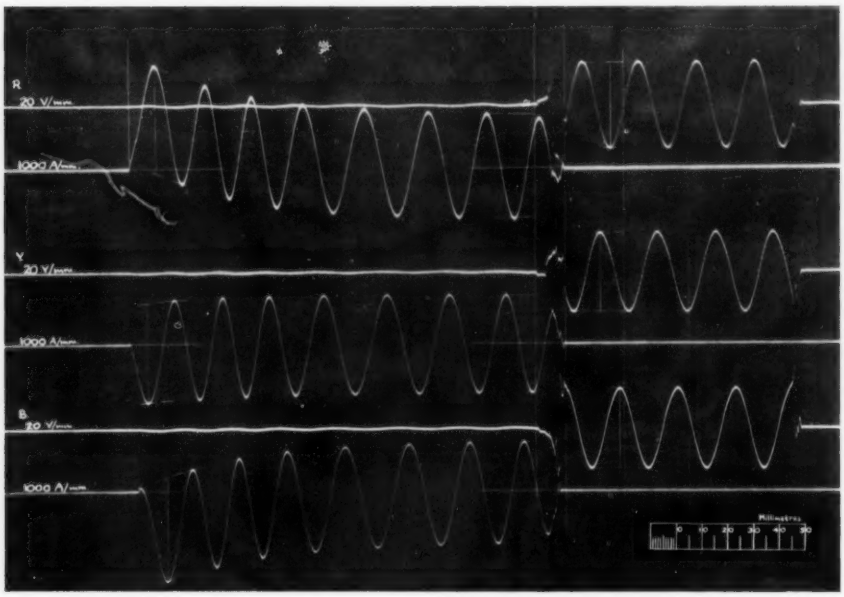


Fig. 5.—Oscillogram of 30% 3-phase "break shot," symmetrical amps 13,300, 400 volts, 9.2 MVA.

better conductivity, while still being less subject to the risk of breakage.

An important feature of the design consists of adequate shunts for connection between the secondary and main contacts for the transfer of the current, without burning of the main contacts. The shunts which are connected to the moving platform member are so arranged that the heavy short-circuit current will tend to increase the contact pressure on the secondary contacts. The current path to the arcing contacts is required to be constructed in such a manner that the magnetic field will direct the arc upwards into the arcing chamber on its formation. Consequently, for maintaining an adequate contact pressure against the effect of the very high short-circuit currents, the contact pressure of the arcing contacts depends upon the pressure exerted by the springs.

To provide additional protection from damage to the main contacts, overlapping insulating baffle plates are inserted between the secondary contacts and the main contacts. Consequently, any gases which may tend to move downwards are deflected, thus preventing the arc from damaging the main contacts when interrupting heavy currents.

A high mechanical speed of breaking is necessary to minimise the energy which must be dissipated and interrupted. This has been achieved in this breaker by making the moving contact arm and its associated members as light as possible, and by using powerful springs to produce initial acceleration. In the higher ranges of short-circuit currents, complete operation, from the time of application of the tripping effect until the extinction of the arc, is achieved in one half-cycle. The normal operation at very low values of the short-circuit current does not ordinarily exceed two half-cycles. Suitable air-dashpot buffers are provided to absorb the shock due to the high speed of the contact arm on opening.

Interrupting Tests.

Single-phase and three-phase short-circuit tests have been made at 400 and 600 volts, 50 cycles. These tests range in current values from a few amperes up to 40,000 amperes symmetrical R.M.S. breaking, and crest values of over 100,000

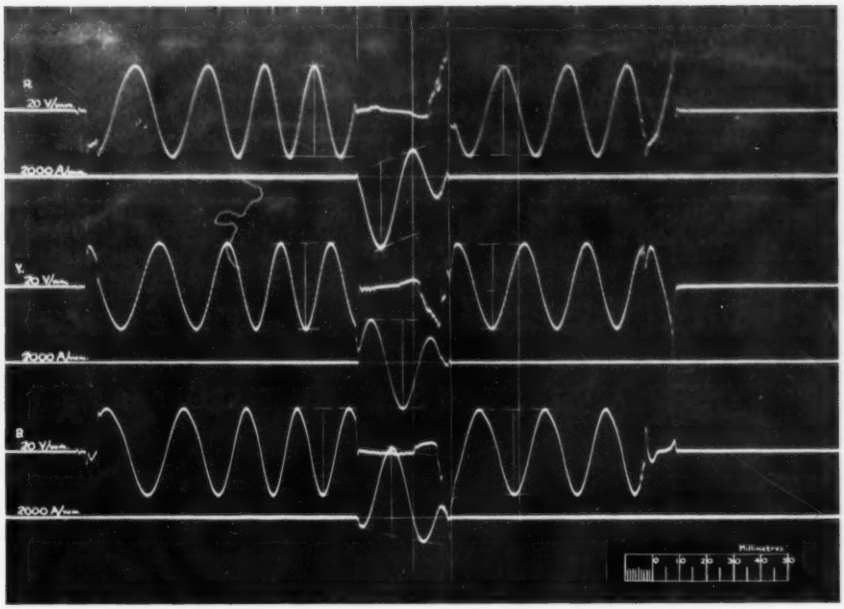


Fig. 6.—Oscillogram of 60% 3-phase "make-break shot," symmetrical amps. 21,800 amps., 400 volts, 14.5 MVA.

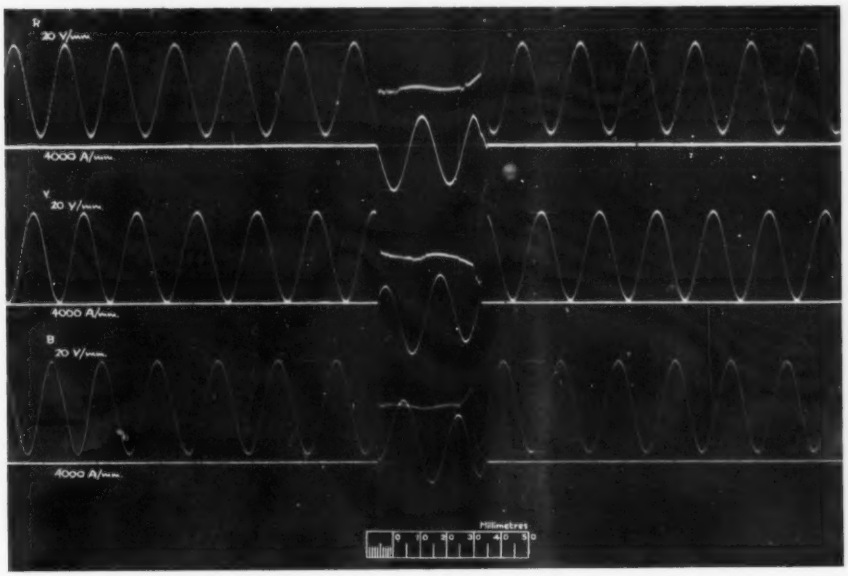


Fig. 7.—Oscillogram of 100% 3-phase "make-break shot," symmetrical amps. 37,000, 400 volts, 25.6 MVA.

Fig. 8.—3-Phase, 400-volt electrically-operated Circuit-breaker Equipment, with Arcing Chambers removed.

amperes have been dealt with on making shots. The oscillograms Figs 4, 5, 6 and 7 show how rapidly and smoothly the arc voltage increases and the effective arc-extinguishing action that is obtained. It will also be seen that the arcing time is limited to approximately one half-cycle whether operating at 10 per cent., 30 per cent., 60 per cent. or 100 per cent. duty-cycle. The fast breaker action provides an overall operating time varying from three cycles at low short-circuit values of current to one and a half cycles at very heavy currents.

Examples of Equipment.

An electrically-operated circuit-breaker equipment, with arcing chambers removed, is shown in Fig. 8 ; all the live parts are enclosed in the sheet-steel housing. The circuit-breaker is mounted on a panel which is hinged at the bottom and arranged to allow a forward movement, while a lever arrangement operated by a detachable handle also serves to close the circuit-breaker if the latter is hand-operated. The circuit-breaker is fitted with back-of-panel contacts, which, with the panel in the normal vertical position, engage corresponding stationary contacts to which the busbars and cable circuits are connected.

Movement of the isolating lever allows the panel about a 10 deg. forward movement, as shown in Fig. 9, which is sufficient for isolation. For inspection and maintenance, arrangements are made so that the panel can be dropped further forward through the front-door opening, to almost

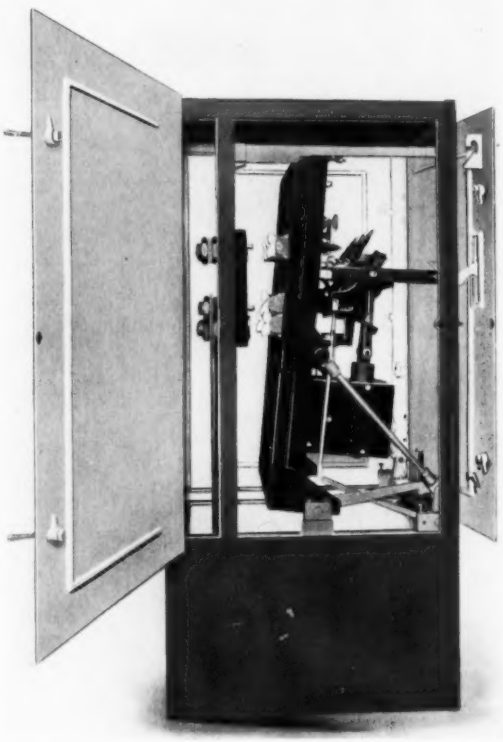


Fig. 9.—Side view, with circuit-breaker in isolating position, of equipment shown in Fig. 8.

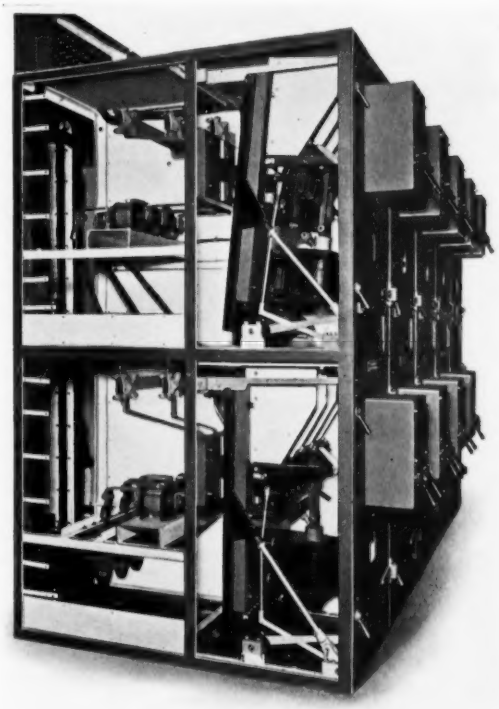


Fig. 10.—Side view of 3-phase 400-volt electrically-operated Circuit-breakers showing double-deck method of assembly.

a horizontal position. Complete mechanical interlocks are provided to give the usual protection against access to live parts and to prevent "making" or "breaking" circuit on the isolating contacts.

The equipments can be built up side by side into switchboards and where space is restricted a double-deck arrangement can be employed, which allows for the circuit-breakers being mounted one above the other. Fig. 10 shows an arrangement of an equipment of this type; the side sheet is removed to show the interior.

Conclusions.

By utilising the new form of arc-interrupting device, in conjunction with a fundamentally improved air-break circuit-breaker, both electrically and mechanically, it has been possible to manufacture breakers of this type comparatively small in size which will satisfactorily and repeatedly rupture currents up to 40,000 R.M.S. symmetrical amperes A.C. or equivalent values of D.C. A complete breaker, electrically operated, is shown in Fig. 11. The noise and demonstration which is usually present with the air-break circuit-breaker when operating on short-circuit has been considerably reduced. The extent of ionised gas or flame has been also sufficiently reduced so that these breakers have a space factor comparable with oil circuit-breakers and can be closely mounted in steel cubicles without the necessity for providing large areas above the breaker for taking care of the gases formed.

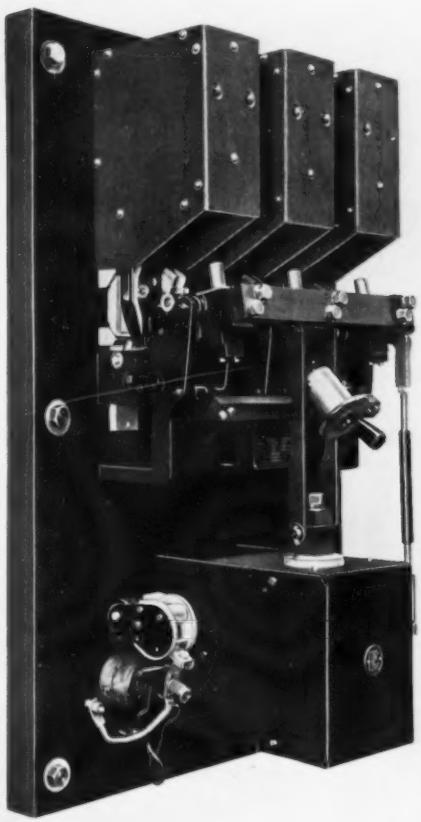


Fig. 11.—Panel-mounted type OB3 400-volt High-breaking capacity Air-Circuit-breaker.

3,300-VOLT AIR-BREAK CIRCUIT-BREAKERS.

In view of the very satisfactory performance of the 400-volt air-break circuit-breakers as exemplified by the large number of units in use, development directed toward the extension of the fundamental principles to higher voltage ratings followed as a logical sequence. Such extension involved a new conception of contact arrangement to incorporate arc transference and also a new conception of a de-ionising chamber capable of dealing with the larger powers and the higher voltages. This development led into new ground, as at the higher voltages higher rupturing capacities became necessary, and this involved means for moving the arc promptly from the sparking contacts to the de-ionising chamber, introducing voltage into the arc in a smooth but rapidly increasing manner, and ensuring speedy positive interruption.

The results of this development are incorporated in a design set forth herein, capable of performing a B.S.S. duty-cycle without requiring liquid di-electric or other form of stored interrupting medium.

Design of Arcing Chamber.

As with the 400-volt chamber, it has been possible in this design to avoid the use of magnetic blow-outs which so frequently introduce complications and difficulties in maintaining a high insulation level. In the design of the chamber for this voltage there are a number of conducting plates of magnetic material. These plates are spaced at intervals of approximately one-eighth of an inch apart and at right angles to the arc. This allows free ventilating space out

Fig. 12.—View from bottom, showing arrangement of Plates in a 3,300-volt Arcing Chamber.

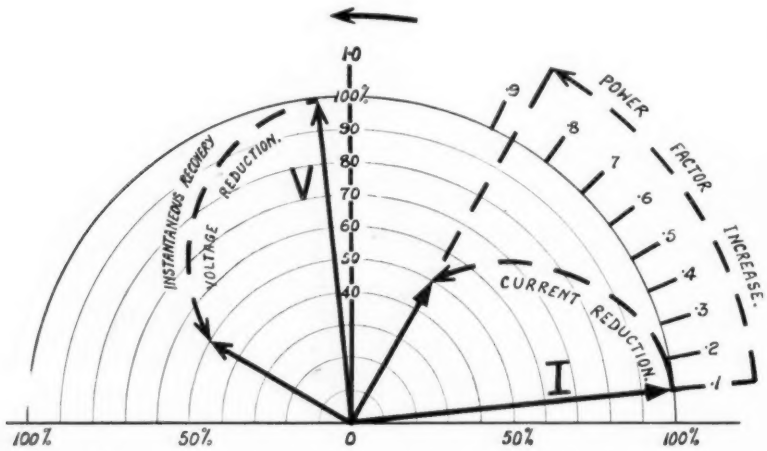


Fig. 13.—Vector Diagram showing change in phase and magnitude of instantaneous recovery voltage and short-circuit current as arc is drawn to extinction.

to the top for the escape of the gases and keeps down the back pressure which would prevent the gas from rising freely. The shaping of the plates at the bottom—see Fig. 12, which has been arrived at as the result of many hundreds of tests, facilitates the movement of the arc from the sparking contacts into the arcing chamber in a smooth and efficient manner. Magnetic control is obtained by self-induction of the plates. At the top of the arcing chamber there are mounted a number of insulated plates with a larger spacing between them, and in this manner they offer no additional restriction to the arc or to the arc gases. This arcing chamber has proved most effective in cooling the gases so that there is very little visible display of ionised arc or gases at the top of the arcing structure.

Unlike the 400-volt operation, where the arc is interrupted at the sparking contacts of the breaker, it was found necessary with this design to incorporate transfer electrodes of good conducting material which extend practically the whole length of the arcing chamber. These electrodes are placed at the extreme ends at the back and the front of the arcing chamber. Some difficulty was experienced, at currents of the order of 300 amperes and below, in controlling the arc and extinguishing it within two or three half-cycles. To overcome this difficulty, small air-dashpots were introduced for buffering the moving contact arms in the " open " position, and which at the same time served to give a very small supply of air to the bottom of the arcing chamber. This was found sufficient to cause the arc to transfer immediately from the sparking contacts to the arcing chamber electrodes, where it was brought under proper control.

When operating on A.C., the arc is interrupted at an early current zero, but the arc drop is not high until the end of the arcing half-cycle. There is normally only one to two half-cycles of arcing at the heavier currents and a maximum of three half-cycles at the lighter currents.

Breakers equipped with these interrupters have been successfully tested up to their maximum short-circuit capacity in earthed enclosures having the top surface only 3 in. above the arc chamber. The chamber is also effective as a silencer and considerably reduces noise. Voltage drop in the chamber is approximately 500 volts per inch R.M.S. alternating current.

It was observed on the 400-volt tests that the

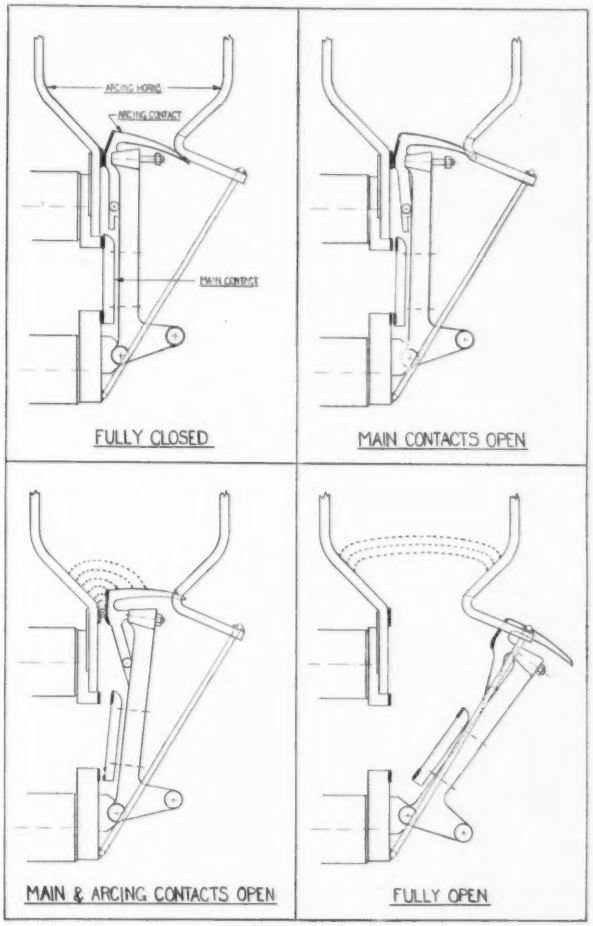


Fig. 14.—Contact opening sequence of 3,300-volt Air-break Circuit-breaker.

operation of the air-break circuit-breaker tended towards an easement in the severity of the circuit conditions. This feature became apparent to a greater extent when testing the 3,300-volt circuit-breaker. The results of this easement are shown in the graph reproduced in Fig. 13. This is a vectorial representation of the inherent easement in severity which is actually effective within the arcing chamber. The diagram is set out with reference to the internal generator peak voltage, which is indicated along the vertical axis as being at each half-cycle of arcing, and is shown as constant in phase position and having a magnitude of 100 per cent. Upon the application of the short-circuit, the initial current in the arc, which takes place at the sparking contacts, is of comparatively low power factor until the arc is transferred to the transfer contacts in the arcing chamber. In the example shown the circuit power factor is indicated as .1 and the initial fault current I is shown at the corresponding angle from the vertical ordinate. At the first current zero after contact separation, an instantaneous recovery voltage, V in the diagram, can appear across the breaker. This vector is only slightly removed from the peak voltage and the magnitude of the instantaneous recovery voltage is therefore approximately proportional to the generator peak voltage, thus submitting the breaker at this instant to the full severity of the circuit. At the subsequent current zero, however, conditions are considerably modified. The current is reduced to approximately half the initial value and the power factor is increased to the order of, say, .8 to .9. As the result of this reduction in phase angle, the second current zero is advanced to a point of reduced instantaneous voltage. This change in the instantaneous recovery voltage in both magnitude and relative phase position is shown in the graph. The reduced value of the voltage is approximately 50 per cent. of the initial voltage and the effect of the severity on the circuit-breaker is actually still further reduced due to the effect of the introduction of the arc resistance in damping the natural oscillations of the circuit.

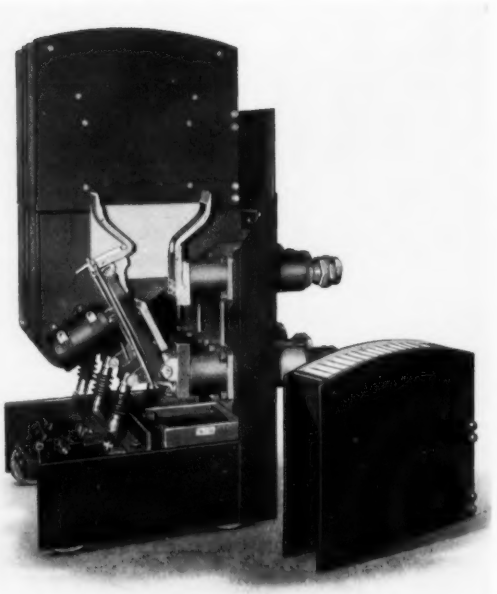


Fig. 16.—3,300-volt Air-break Circuit-breaker—open position.

Fig. 15.—3,300-volt Air-break Circuit-breaker—closed position.

In this respect it should be remembered that the arc of an oil circuit-breaker introduces very little resistance with practically no improvement in phase angle and therefore such a breaker must withstand the full shock of the circuit recovery characteristics. It will be noticed the oscillogram shown in Fig. 18 indicates the effect of the phenomena referred to in Fig. 13. Herein it will be observed that in addition to the reduction in voltage there is approximately 50 per cent. depreciation in the current loop. It is also shown in general form in this oscillogram that the phase angle as the current approaches its final zero is closer to the voltage than is indicated by the phase angle at the peak of the last current loop.

CONSTRUCTION.

It was necessary slightly to modify the three-stage arrangement used for interrupting the arc in the construction of the 400-volt breaker, and while the arc is extinguished in the same number of stages the sequence is slightly varied. As the order of current to be interrupted was approximately the same as that in the 400-volt breaker, it was possible to retain the same type of operating mechanism, it being only necessary to introduce suitable insulated operating links for the increased voltage. The contact arrangement, shown in Fig. 14, consists of three stages. The first stage is the main contacts, which serve only to carry the load current; the second stage the arcing contacts which serve to protect the main contacts from deterioration during interruption and at the same time interrupt the arc. The moving arm carries the spring-loaded arcing contact as well as the main contacts. The arcing contact passes through a slot in the base of the front electrode in the arcing chamber, and it has an extended tail, which, while in the closed position, maintains the arcing contact in close proximity to this electrode. This arrangement facilitates the operation of the third stage of transferring the

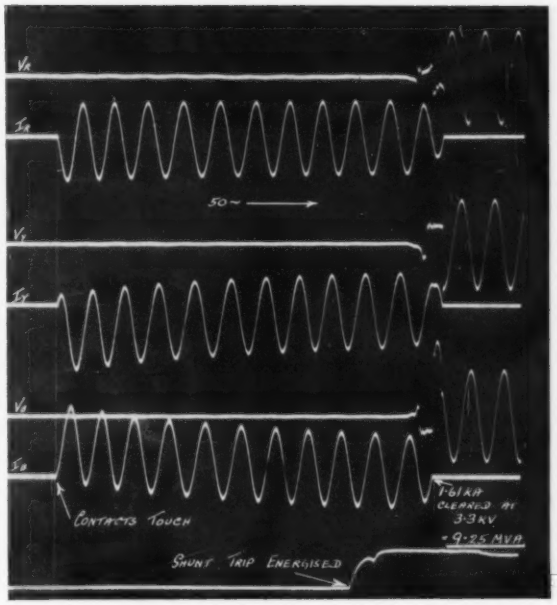


Fig. 17.—3-Phase 3,300 volts 10% "break shot" symmetrical.

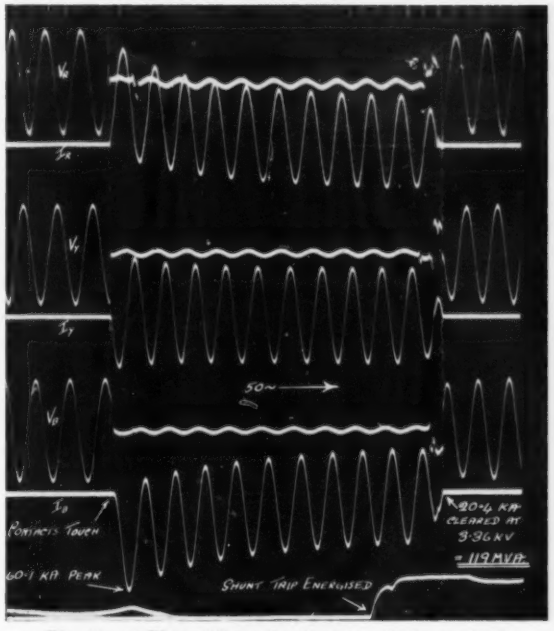


Fig. 18.—3-Phase 3,300 volts 100% "make-break shot" symmetrical.

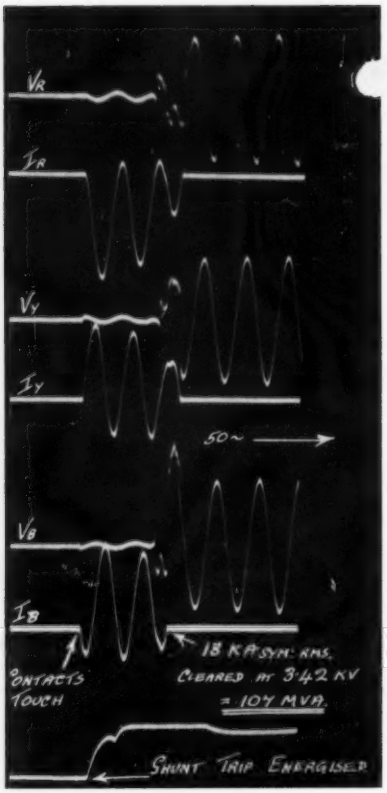


Fig. 19.—3-Phase 3,300 volts 100% "break shot" asymmetrical.

arc from the moving arcing contact to the front electrode in the arcing chamber at an early period in the formation of the arc. The front electrode in the arcing chamber is also directly connected to the bottom terminal stud of the circuit-breaker. The top terminal stud is connected to the back electrode ; thus the final arc interruption is effected in the arcing chamber between the two electrodes. Since the electrodes are made of good heat-conducting material, rapid movement of the arc in an upward direction is facilitated, causing the minimum deterioration to the materials used in the construction of the arcing chamber. Figs. 15 and 16 show the breaker, with the arcing chamber removed, in the closed and open positions respectively. The arcing chamber can be removed by releasing two bolts, which is a very simple operation and when carried out exposes to view the whole of the contact system.

The entire construction provides a very simple design, unusually neat in appearance and effective in operation.

Interrupting Tests.

Single-phase and three-phase short-circuit tests have been made up to voltages as high as 5,000 volts, 50 cycles. These tests range in current values from a few amperes up to over 20,000 amperes symmetrical R.M.S. breaking, and crest values of current of over 60,000 amperes have been dealt with on making shots. The oscillograms Figs. 17, 18 and 19 show how rapidly and smoothly the arc voltage increases and the

Fig. 20.—3,300-volt 3-Phase 100 MVA. Air-break Circuit-breaker mounted on withdrawable Truck-type equipment.

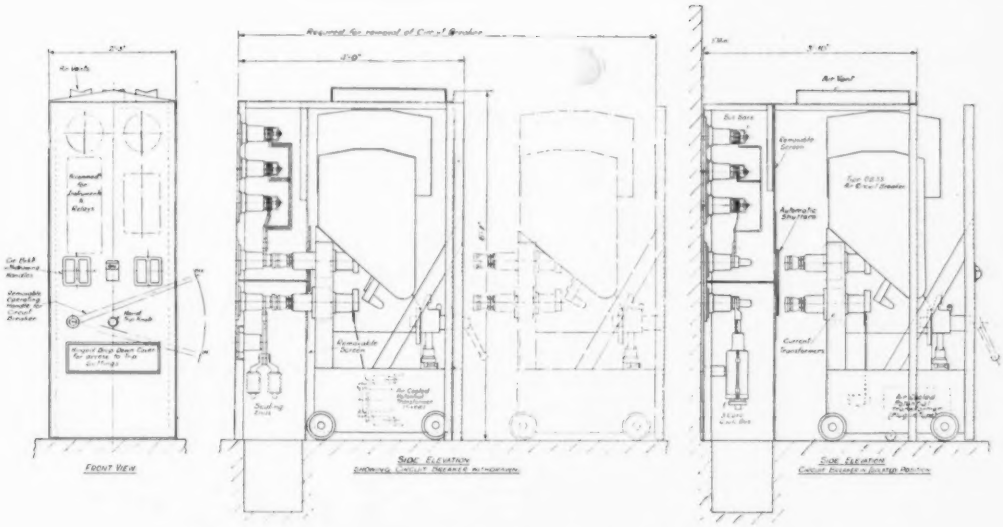


Fig. 21.—Typical arrangement of Truck-type unit with 3.3 kV. type OB/33 Air-break Circuit-breaker.

effective arc extinguishing action which is obtained. The arcing time is limited to approximately two half-cycles at both the 100 per cent. and 10 per cent. duty cycles. The breaker action provides an overall operation time of approximately 5 half-cycles.

Examples of Equipment.

The circuit-breaker can be mounted in totally-enclosed sheet-steel housings, and the usual form is of the familiar withdrawable truck-type construction, which permits of the ready withdrawal of the unit for inspection and maintenance purposes. A very compact example of this type of unit is shown in Fig. 20. Alternatively, the breaker can be mounted in sheet-steel cubicles, suitably interlocked and without the withdrawal feature. In both cases, complete mechanical interlocks are provided to give the usual protection against access to live parts and to prevent "making" or "breaking" circuit on isolating contacts. The switch equipments can be built up side by side into switchboards. The complete equipment is shown in Fig. 21.

Conclusions.

This new type of air-break circuit-breaker, by cooling and lengthening the arc and by efficient means of arc transfer, adds resistance to the circuit as the arc is extinguished and consequently the rates of rise of recovery voltage are held to a harmless value. The introduction of a puff of air to the bottom of the arcing chute at the instant of arc interruption has demonstrated that the breaker is suitable for opening the lowest possible values of current at very low power factors, such as are met with as magnetising currents in power transformers. The "English Electric" circuit-breaker has demonstrated on endurance test that it has a long and economical life, provides reliable circuit control, and that the arc control is such that arc gases and transference of interrupting maximum current values are reduced to a minimum. The physical arrangement allows of the use of the circuit-breaker in metal-enclosed compartments without having to allow excessive clearance for dissipation of the arc gases.

Electrical Plant for Testing Internal Combustion Engines.

By W. E. STREETE, Manager Plant Sales.

The enormous expansion in the use of the internal combustion engine during the last thirty to forty years has led to an increasing demand for suitable electrical machinery for testing these engines, both from the point of view of obtaining data for experimental purposes as well as for routine production work.

The increase in size of petrol engines, particularly for aeroplane work, has also been a contributory factor to the use of electrical testing plant. The property of an electric machine, which permits it to generate electrical energy when driven by mechanical means and to give mechanical power when supplied from a source of electricity, has been found by engine designers to give the ideal means of obtaining reliable data on the performance of individual engine parts, as well as the complete engine.

The principle of obtaining the torque exerted by an electric motor, or other prime mover, using a brake drum with a torque arm and balance weights is familiar to all and this principle of measuring torque is used to a large extent in the present-day testing of internal combustion engines. This method is applied in two ways : firstly, by means of some form of water brake and, secondly, by an electric dynamometer. The water brake is used very considerably for production testing, since it is cheaper in first cost than the electric machine, but it depends for its use on a supply of water and the mechanical energy from the engine is transformed into heat and is therefore wasted. In some cases the water is cooled and re-circulated, but nevertheless the energy is still lost. On the other hand, electrical energy obtained from a dynamometer can be used to supplement the factory supply, either direct or through suitable converting plant. Another advantage of the electric as compared with the hydraulic dynamometer is that it can be used as a motor for starting the engine or for running-in purposes and, furthermore, remote control can be effected.

In the case of large engines, where it may be difficult to dispose of the full output from a dynamometer—and this applies especially in the case of a bank of such engines—a combination of water brake and electric dynamometer has been used, the motoring condition being carried out by the dynamometer, and the loading condition by the water brake.

In addition to the practicability of measuring torque by means of an electrical machine, it can also be used in a simple manner either as a motor to indicate the power taken to run-in an engine, or as a generator to absorb the output of an engine on test, merely by measuring the power taken or given on suitable indicating instruments. This method is obviously less accurate, however, than that involving the use of torque readings.

Electrical machinery can therefore be used for the following two methods :—

(1) Machines of the fixed-frame type with suitable instruments for measuring their electrical input and output.

(2) Machines of the swinging-frame type with torque arm and some form of weighing gear for measuring the torque taken or exerted by an engine.

These machines are commonly known as dynamometers, although this description more correctly applies to the machines in the second category.

The following description is confined to the use of direct-current dynamometers, as owing to the more flexible speed and load control obtainable with D.C. machines as opposed to A.C. machines, this type has almost invariably been used up to

the present. The increase in use of variable-speed A.C. motors of various types will, no doubt, cause consideration to be given to the use of A.C. dynamometers, particularly as in the majority of cases alternating current is available, whereas direct current has usually to be specially provided for the purpose.

The type of electric dynamometer to be used depends to some extent on the engine test routine ; for instance, some classes of engine are run in under their own power, whereas for others it is required that they are driven by some other form of motive power, and it is in the latter case that the electrical dynamometer is particularly useful, since it may be used as a motor for starting and running-in purposes, and then changed over to act as a generator by means of which the engine can be loaded.

Engine-test stands fitted with fixed-frame dynamometers must be provided with measuring instruments, either ammeter and voltmeter or kW./H.P. meter. In all such cases it is necessary to have a range of efficiency figures for various loads taken at various speeds within the working speed range of the engine. The kW./H.P. meter can be calibrated in conjunction with an efficiency curve, but this will only be accurate for a certain speed ; nevertheless, a series of corrections can be supplied for other speeds.

The swinging dynamometer, on the other hand, enables the torque to be read at any instant, at any speed and load, since for a given torque at the shaft there will be an equal and opposite reaction on the dynamometer frame, and this reaction is measured on the weighing gear. It is important to note that since the whole machine is swinging, the torque measurement takes into account the friction and windage losses in the machine. The H.P. is derived from the formula :—

$$\text{H.P.} = \frac{2\pi \text{ N.T.}}{33{,}000}$$

where N. = the speed in r.p.m. and
T. = the torque in lbs./ft.

Fig. 1 shows a machine of the swinging-frame type, from which it will be seen that the construction is similar to that of an endshield machine with the frame feet omitted, but the carcase is capable of rotation in the trunnion bearings, which are mounted on a suitable bedplate.

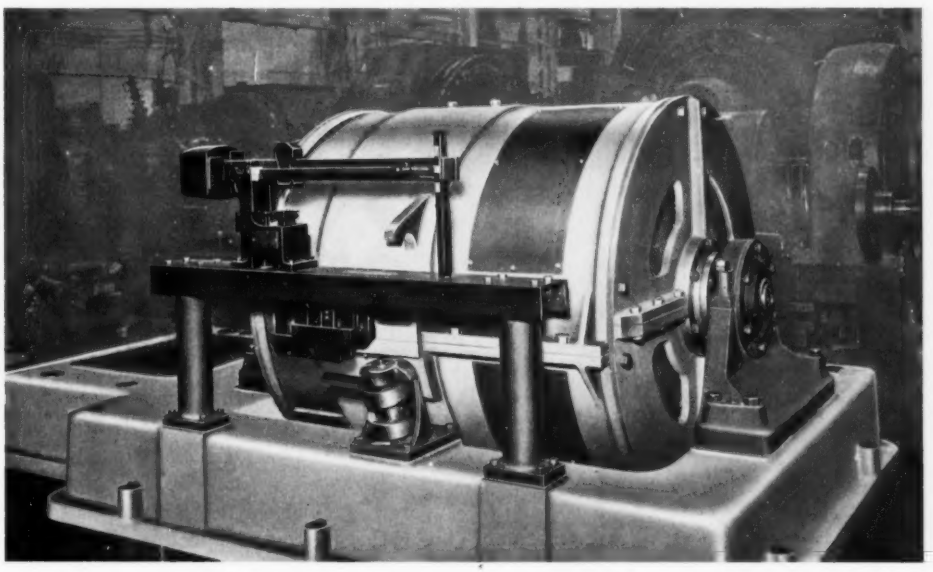


Fig. 1.—"English Electric" Swinging-frame type Dynamometer.

A locking gear is provided to lock the frame solidly when no readings are being taken in order to prevent undue wear of the weighing gear. This locking gear can be either operated by means of a pedal or a handwheel or other simple device to limit the movement of the frame. The weighing gear commonly takes the form of an ordinary brass dial spring balance, calibrated in pounds, but since the spring of the balance tends to oscillate, an absolutely steady reading is not obtainable. Nevertheless, the results may be sufficiently accurate for routine purposes.

For precision work, however, the use of the steelyard with sliding weights is essential and it is not unusual to find in a factory, fixed-frame dynamometers used for production testing and one or more machines of the swinging-frame type, with the beam-weighing gear for experimental and type-testing purposes. Another advantageous arrangement is the use of all swinging-frame dynamometers ; those for production testing would be fitted with spring balance, and those for experimental work and type-testing equipped with the sliding-weight type of weighing gear. It is desirable that the weighing gear should have as low inertia as possible.

In some cases the spring balance is used in addition to the beam, the former being suitable for quick readings, and also to act as a buffer to take up sudden shocks. An oil-dashpot may also be used for the latter purpose, when it is generally attached to a projection on the frame. In the formula referred to above, the torque T can be read off the sliding weight scale, but if a spring balance is used, T must be obtained from the product of the reading of the spring balance by the radius of the point at which the torque is measured. The dynamometer is also provided with a tachometer generator and speed counter, the latter being for accurate determination of speed by counting against a stop watch.

It is desirable for the dynamometer to be direct-coupled to the engine, as the interposing of a gear box adds additional losses which cannot be measured. In view of present-day high engine speeds, the mechanical construction of the dynamometer armature requires careful consideration and may necessitate the use of shrink rings on the commutator.

In order to keep the diameter of the armature as small as possible, it has been found advantageous to employ higher temperature rises than those common in the industrial field ; for instance, it has been found possible to design a machine with an output of 300 h.p. at 3,600 r.p.m., or 150 h.p. at 6,000 r.p.m., in a single frame with a temperature rise not exceeding 105° C. by resistance. This temperature rise is nothing unusual, however, as it has been standard for traction motors for a considerable number of years.

The field system of the dynamometer should be accurately balanced on its own trunnions, and the balance should be such that if the frame is moved slightly from its normal position, it will remain in the new position.

It is important that the ventilating air in the dynamometer is suitably controlled by baffles, so that there is no disturbing torque reaction on the frame from this source.

For swinging-frame dynamometers it is obviously necessary to supply flexible connections for the main and field leads and, in the case of the main connections, these can be conveniently made by means of a number of very thin copper strips or of copper braid.

In the case of aeroplane engines, the supercharger is usually tested separately from the engine and, since the test routine consists of running the supercharger over a wide range of speed, a variable-speed D.C. motor forms a convenient means of doing this.

It is frequently required, however, to take accurate torque readings for this test, and therefore the swinging-frame dynamometer is again used. The tendency in aeroplane engine construction is towards testing as many individual parts as possible, all of which necessitate a variable-speed drive, and electrical machinery provides a convenient means for doing this. An instance of this is the rear cover portion of a supercharger, which, for test purposes, is driven by a D.C. motor, the load being obtained by means of a generator coupled to the rear cover, thus giving variable speed and variable loading.

A D.C. motor also provides a suitable means of carrying out acceleration tests on certain engine parts, and this method is also adopted in the aeroplane engine industry.

The amount of control gear required for use with the dynamometer naturally varies with the type of electric supply available, the test routine and the degree of automatic control required.

In the simplest case, where a D.C. supply is available, the dynamometer can be arranged as a motor with a relatively wide speed range by means of shunt field control, so as to cover the normal working range of the engine to be tested and, below this speed, control can be obtained by series resistance. A case in point is a 500 h.p. dynamometer with a shunt speed range of 900/1,800 r.p.m. with series control down to 400 r.p.m. The output required falls off at low speeds, especially in the case of a supercharger, so that series control is not unnecessarily wasteful.

Again, when a D.C. supply is available and the engine is to be loaded, the dynamometer can be arranged to generate and supplement the factory supply and, in the case of one factory within the author's experience, a current of about 500 amps. is available from the test stands. Since the engines are under a steady load for some hours, this condition enables some of the generating plant in the factory power station to be shut down for long periods with resulting saving in power costs. It has been found that the cost of the power saved in this way is sufficient to pay for the cost of testing.

For installations in a production test house, the control gear should preferably be of the dead-front cubicle type and for the smaller engines a drum controller may be used for the series part of the speed range, but for larger engines a contactor equipment is usually necessary. It is useful to provide, in the case of petrol engines, an ignition relay with the control equipment, which is interlocked with the circuit breaker, so that the engine is shut down on failure of the D.C. supply in order to prevent excessive overspeed

When the only supply available is alternating current, the first question to be settled is the type of converting plant to be used, which may either be a rectifier, rotary converter or motor-generator set. Where the supply is direct current, and no regeneration is possible, as in the case of a bank of supercharger test stands, rectifiers can be used; but even so, care must be taken to ensure that the speed of the dynamometers is reduced slowly, so as to prevent high induced voltages. If only one dynamometer is to be supplied, a Ward Leonard motor-generator set forms an ideal method of obtaining speed and load control, and this permits regeneration back

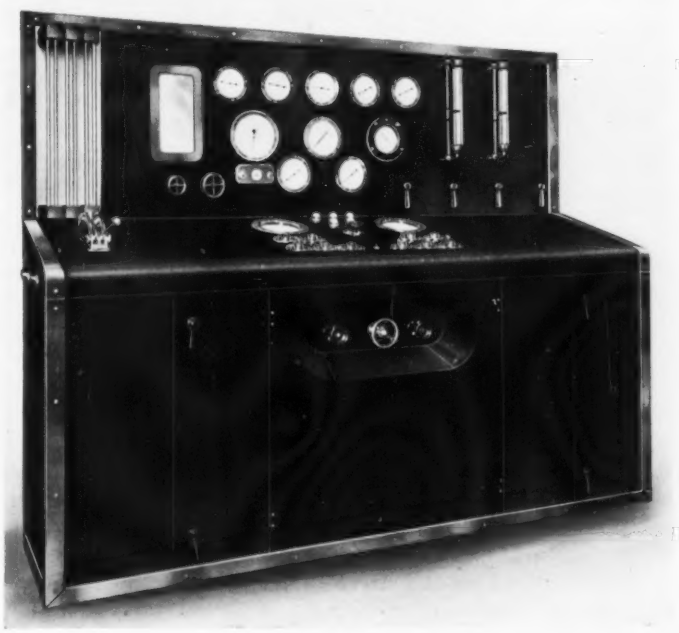


Fig. 2.—Combined engine test and Dynamometer Control Desk for superchargert esting.

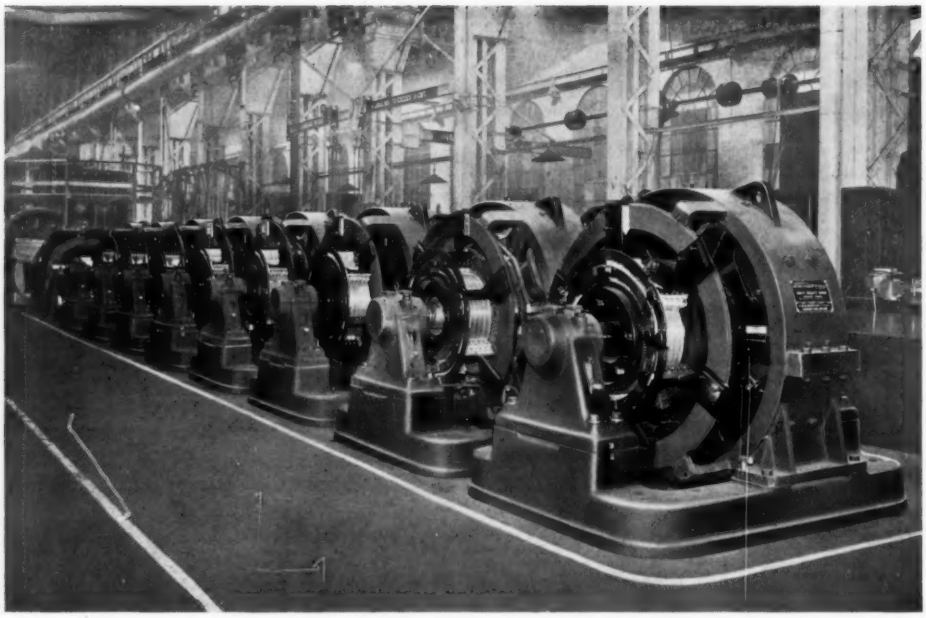


Fig. 3.—A number of "English Electric" variable-speed Fan Motors for supplying cooling air when air-cooled engines are tested.

on to the A.C. system, together with some correction of the power factor of that system if desired.

A single motor-generator set may be used with a bank of dynamometers, but in this case the speed and load variation must be obtained by shunt and series control. Rotary converters can be used for regeneration, but both these and rectifiers suffer from the disadvantage that fluctuations of line voltage reflect through to the dynamometer and result in speed variation at a given setting.

With a motor-generator set including a synchronous driving motor, the D.C. voltage is independent of the supply voltage and, by level or over-compounding the generator, the load drop in the feeders can be counteracted, so that a constant voltage is available at the dynamometers. The engine test instruments and controls are generally mounted independently of the dynamometer controls, but in some cases the two are combined on one desk. Fig. 2 shows an example of the latter type used for supercharger testing.

This control gear is arranged for remote control, the contactors being separately mounted. In this instance the series part of the speed range is obtained by a selector switch operating the various contactors, but individual push buttons can be used instead of a selector switch.

For quantity production it is possible to design the control gear so that the operation is semi-automatic, the testing sequence being so interlocked that, for example, the engine cannot be put under load until it has been eased out to a certain degree by motoring. When the torque has decreased to a predetermined figure, arrangements can be made automatically to increase the engine speed, suitable protection being provided against seizure of the engine.

When the engine is loaded on the dynamometer two or more load conditions can be provided and, if the current corresponding to the selected con-

dition is exceeded, the engine is shut down.

Another application of electric motors is that of large air-cooled engines, which require the provision of variable-speed fans for supplying the necessary cooling air. Fig. 3 shows a number of such machines.

Summarising, the uses of electrical plant for engine testing are as follows :—

(1) Motors for starting and running-in purposes.

(2) Dynamometers, both fixed and swinging-frame type, for supercharger testing and engine testing.

(3) Motors for driving fans for supply of cooling air.

Such machines need control gear, converting plant or transformers and switchgear, etc., all of which are manufactured within The English Electric Company's organisation.

Some Notes on Fuel Injection and Combustion in Compression-Ignition Engines.

By G. H. PAULIN, M.I.Mech.E., M.I.Mar.E.—Chief Engineer, Internal Combustion Department.

Recently, an American authority, in a survey of the last "Five Years' Progress of Oil and Gas Power," said, "Undoubtedly, the Diesel engine is recognised to-day as one of the most economical and reliable prime movers known, and is fast taking its place in applications for which it seemed unsuited a few years ago."

In the case of the older, slow-running, air-injection engines—the true Diesel engines—the fuel injection system played an important part, but with the modern airless injection engine, running at very much higher speeds, the design of the fuel injection system is the most important factor contributing to this economy and reliability. With an incorrectly or even indifferently designed injection system, an otherwise soundly constructed engine will fail both in regard to economy and reliability. Poor cylinder conditions are inimical to economy from the fuel consumption point of view, and the excessive temperatures resulting from high consumption soon react unfavourably on reliability and maintenance, and so, ultimately, again on economy.

The conditions required for the successful injection of fuel, and the combustion processes following injection, are complex. In recent years considerable work has been carried out in an endeavour to establish the essential conditions. In Britain, Ricardo, Davies, Giffen, Rowe, Egerton and Drinkwater, Stansfield and Le Mesurier have made valuable contributions to the accumulating knowledge of the subject; in America, Rothrock, Schweitzer; on the Continent, Sass, Neumann, Mehlig, Holfelder, Boerlage and Broeze.

The complexity of the variables (some twenty or more) involved has necessitated that much of this work has been of an empirical character. Nevertheless, these patient studies and investigations have contributed very largely to the remarkable efficiency of the present-day compression-ignition engine. Most of the work of the investigators has been done in laboratories, and it has been the task of the engine designer to apply the knowledge so gained to the practical field of the workshop.

It is not necessary for the operator of an oil engine to have full knowledge of what is happening in the injection system or in the engine cylinders. The detail construction of both is fixed by the designer, and the operator can do little in the way of altering the conditions. All that is necessary on his part is adequate maintenance of the components concerned. The references made in this article, however, should, it is hoped, aid in a conception of the general principles involved in the injection and burning of the fuel.

Injection of Fuel.

Detail consideration of all phases of fuel injection and combustion is impossible here, and

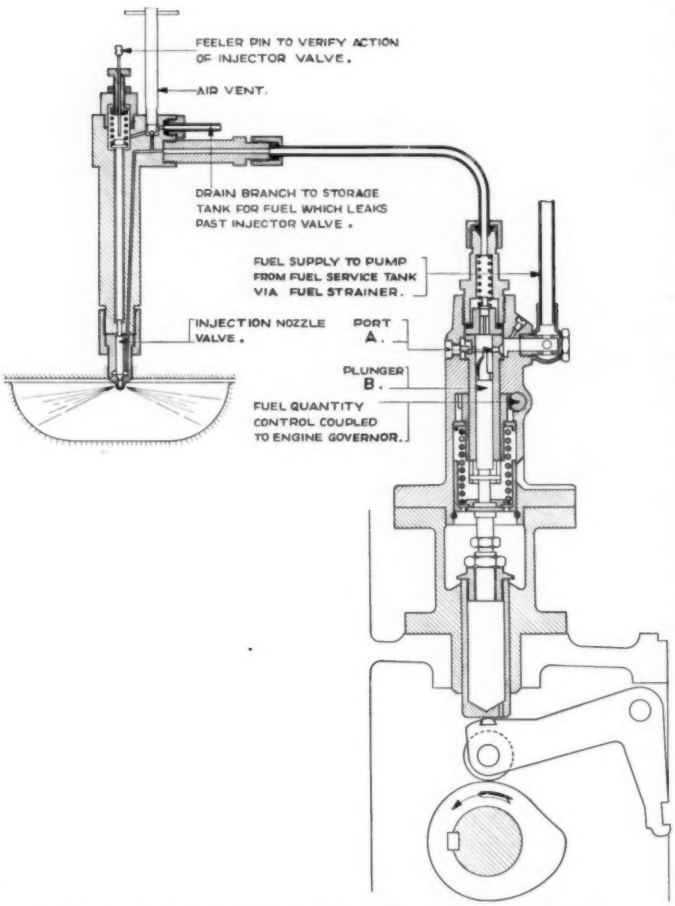

FEELER PIN TO VERIFY ACTION OF INJECTOR VALVE.
AIR VENT.
DRAIN BRANCH TO STORAGE TANK FOR FUEL WHICH LEAKS PAST INJECTOR VALVE.
FUEL SUPPLY TO PUMP FROM FUEL SERVICE TANK VIA FUEL STRAINER.
INJECTION NOZZLE VALVE.
PORT A.
PLUNGER B.
FUEL QUANTITY CONTROL COUPLED TO ENGINE GOVERNOR.

Fig. 1.—Typical arrangement of Fuel Pump and Injection Valve.

it is proposed, therefore, to deal only with the salients. Fig. 1 shows a diagram of the essential features of the injection system for one cylinder. Each cylinder of a multi-cylinder engine has a set of equipment as shown. In addition, there is the fuel service tank with strainer which supplies fuel to the inlet connection on each fuel pump.

The sequence of events in the actual injection of the fuel is, briefly :—

With closure of the port A by the upward moving plunger B, the fuel in the system up to the nozzle valve is under compression. Further movement of the plunger increases the pressure in the system to the point where the nozzle valve lifts. Injection now begins and the pressure in the system is controlled from this point until the end of the injection period, by the cross-sectional area of the holes in the nozzle tip and the velocity of the moving pump plunger.

It is necessary, in order to regulate the amount of fuel delivered to the cylinder, to have some means for varying the effective stroke of the pump plunger. Various courses have been followed to achieve the same object, but the best known and simplest is the system whereby a constant plunger stroke is used, with by-pass or "spill" controlled by the engine governor. The classic example of this type of pump is that developed by Robert Bosch, and this pump is in almost universal use, except for the largest sizes of engines.

Any fuel pump, with its injection valve, constitutes an extremely high-class piece of equipment. The greatest possible precision is essential in its manufacture. To realise the duty these parts are called upon to perform, it is necessary to appreciate that, for example, in the Company's H-type engine, the pump and injection valve, at engine full load, deliver 0.0003 lb., or 0.00945 cu. inch of fuel, 750 times per minute, at a pressure of several thousand pounds per sq. inch. The time in which the injection takes place is 0.0022 sec. In this period the oil in the system is compressed, the injection valve opens and closes, inflammation of the fuel occurs and combustion is completed. In order to meet the purists, "more or less" might be added after the word "completed."

To illustrate more clearly the duties the injection equipment has to carry out, Fig. 2 has been reproduced. In this illustration

SPHERE 0·262 "DIA. SPHERE 0·175 "DIA.

Fig. 2.—Volumes of Fuel per injection at full and no loads respectively.

the quantities of fuel injected per cycle have been shown full size. A is the amount injected at full load, and B the no-load injection.

Combustion of the Fuel.

Knowledge of the actual processes of combustion is very incomplete, although a good deal is known of the conditions necessary to bring it about and to make it as efficient as possible. To begin with, the temperature of the cylinder air charge has to be sufficient to cause spontaneous ignition of the injected fuel charge. The more or less generally accepted theory of fuel combustion in the compression-ignition engine divides the process into three major phases. First, an ignition delay period during which the surface of each individual droplet of fuel is heating to a temperature sufficient for auto-ignition. Secondly, a period of very rapid burning of the droplets which have accumulated in the combustion chamber during the ignition delay period, and thirdly, a phase during which the fuel burns almost as rapidly as it enters the combustion space.

Fig. 3 shows part of an indicator diagram on which A is the point of beginning of injection, B is the point at which the pressure rises above the compression curve following on the initiation of general combustion, while C is the maximum pressure developed in the cylinders. A,B is the ignition delay or lag.

The ignition delay period is dependent on a number of inter-related factors—air temperatures in the cylinder during the period of ignition delay, the mixing of the fuel with the oxygen necessary for combustion, and the ignition value of the fuel (cetane number).

Increase of air temperatures occurring in the cylinders at the beginning of fuel injection decreases the ignition delay, and it will be clear that this is in practice largely a matter of compression pressure. Again, too early injection introduces disadvantages in that the fuel enters the combustion space before the compressed air charge in the cylinder reaches adequate temperatures. This results in a greater ignition lag and an increased rate of pressure rise which in turn is the cause of combustion knock. In the high-speed compression-ignition engine this question of "knock" has been one of the major problems, and considerable work has been carried out by the big oil suppliers in developing fuels with high ignition qualities for use in high-speed engines; that is, fuels giving the shorter delay periods. With the slower speed engines the ignition delay is not of such importance. As the delay period is a function of T (temp.), and substantially constant with regard to time, the reason for this will be apparent.

Delay period has probably been the subject of more research on the part of fuel technologists

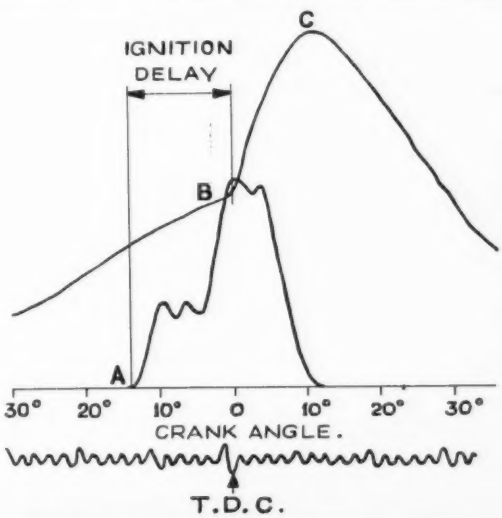


Fig. 3.—Diagram taken with Cathode-ray Indicator.

than any other characteristic of liquid fuel. It has been suggested by Sass that to achieve good combustion, 20 per cent. of the fuel droplets should be not larger than 0.0002 inch, 30 per cent. not larger than 0.0006 inch, and none larger than 0.002 inch diameter. The size of these droplets has actually been measured. Atomization, as represented by such droplets, is considered possible with an injection pressure of 4,000 lb./sq. inch, and an orifice diameter of 0.024 in. The combustion in an actual engine cylinder, however, is complicated by the fact that appreciable penetration of the air charge by the spray is essential and that with fine droplets penetration is prejudiced, while with droplets too large, auto-ignition is delayed or may, in extreme cases, be prevented. As a result of exhaustive research it has been accepted generally that the conditions under which the oil droplet is heated are important factors in the ignition process. Temperature and density of the compressed air charge, relative motion of the air and the fuel, and the size of the droplets determine largely the rate of heat absorption during the ignition delay period. The interval of time up to initiation of burning, or the delay period, is mainly concerned in the heating of the surface of the droplet to a condition where combustion begins. When the surface of some of the droplets has been heated to sufficiently high temperature, in the presence of air accelerated decomposition and oxidation reactions occur, and it is the localized heat evolution resulting from these oxygen-fuel reactions that causes the actual nuclear ignition or inflammation. The ignition itself is of extremely short duration. After a nuclear flame has once formed, ignition proceeds rapidly throughout the remainder of the fuel-air mass. Neumann has pointed out that the time required for these initial reactions constitutes the major part of the ignition delay period.

During the second phase of the combustion cycle, the fuel which has accumulated in the combustion chamber during the delay period burns with great rapidity and produces a rapid increase in cylinder pressure. Evidently, if the ignition delay period has been relatively long, a large amount of fuel will have accumulated, which, when ignited, will cause a very rapid rise to a high cylinder pressure. The amount of fuel accumulating will, manifestly, depend upon the quantity injected during the delay period. It is then obvious that maximum cylinder pressures and smoothness of operation are controlled very largely by the first two phases of combustion described. During the third phase the fuel burns completely and almost as rapidly as it is injected. In this phase the rate of burning and cylinder pressure conditions are controlled by the rate at which the fuel is injected.

The figures quoted earlier, in connection with the H-type engine, give some idea of the precision with which the injection equipment must operate. Other features of the engine must be co-related very precisely in order to enable the fuel pump to function correctly as a measuring instrument, and the injection nozzle to introduce the fuel in the way required.

Wave Action in Fuel Pipes.

With the exception of those systems having very short pipes between the fuel pumps and injection valves, it has been found essential to take into account the wave transmission of pressure impulses along the pipe. It was this knowledge which dictated the location of the fuel pumps on the K and L-type engines built at the Company's Rugby Works. In both these engines the pipes between the fuel pumps and injection valves are only a few inches in length. This feature has ensured a complete freedom from the complications and difficulties arising from uncontrolled wave action.

In the case of the Fullagar engines the case was very different. In the original proposals (1931) for the airless injection model of these engines it was intended to group the fuel pumps transversely at one end of the engine. This made an attractive lay-out and eliminated the camshaft. On the other hand, the arrangement involved very long pipes between the pumps and injection valves. Two problems of major degree arose :—

(*a*) Excessive pressure drop in the delivery line.

(*b*) Wave action in the delivery line.

The former could be minimized by increasing the diameter of the pipes, but this course led directly to difficulties arising out of the much increased volume between pump and injector. In the case of the eight-cylinder engine the pipes were some 30 ft. long.

The question of wave action was investigated in detail, and it is interesting to note that the methods then used were basically the same as those adopted by Giffen and Rowe in their researches in 1938.

It is impossible, in an article of this description, to touch more than very briefly on the propagation of pressure waves. Referring to Fig. 1, the instant the compression of the fuel in the delivery line begins, a pressure wave is propagated. The speed of propagation is substantially that of sound in the medium involved. Using the familiar expression :—

$$V = \sqrt{\frac{Kg}{\rho}}$$

where V = velocity

K = the bulk modulus of the oil suitably modified to include for elasticity of piping

ρ = density

the speed of propagation is approximately 4,400 ft. per sec. In the case of very small pipes, such as those used on the H-type engine, the speed of propagation is reduced by the viscous drag on the walls of the pipe. Some 6 per cent. difference has been shown to exist between the two sizes of pipe involved, on the one hand in the H-type engine, and on the other in the R-type Fullagar, due entirely to the different bores of the pipes.

The wave of pressure travels along the pipe, having set in motion the oil along the length of the pipe, and is reflected at the nozzle. The nozzle valve may or may not lift, the effect of the wave impulse depending upon the relation of the valve spring pressure to that of the wave impulse. The effect of this wave action may be very serious. In the case of a condition of resonant waves, secondary openings of the nozzle

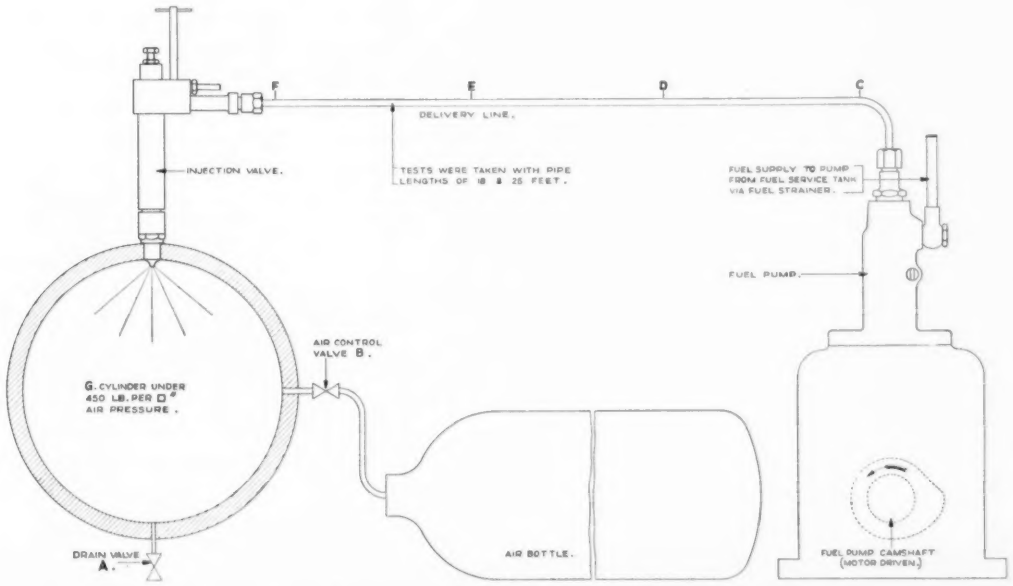


Fig. 4.—Arrangement of Test Apparatus.

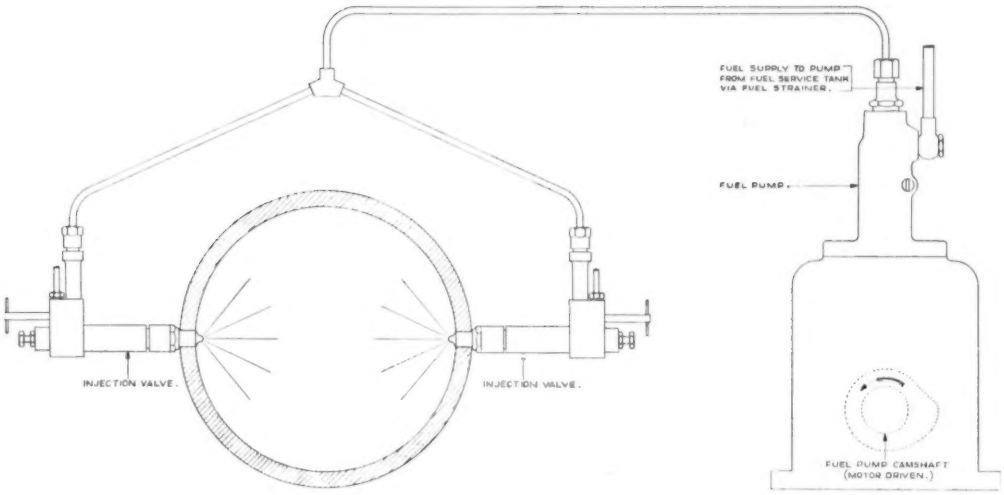

FUEL SUPPLY TO PUMP FROM FUEL SERVICE TANK VIA FUEL STRAINER.
FUEL PUMP.
INJECTION VALVE.
INJECTION VALVE.
FUEL PUMP CAMSHAFT (MOTOR DRIVEN.)

Fig. 5.—Arrangement of Test Apparatus.

valve may easily result. In view of this and the long lengths of piping required for the original Fullagar engine scheme, a complete experimental investigation was carried out to check the theoretical analysis mentioned earlier, and which indicated the likelihood of serious wave effect.

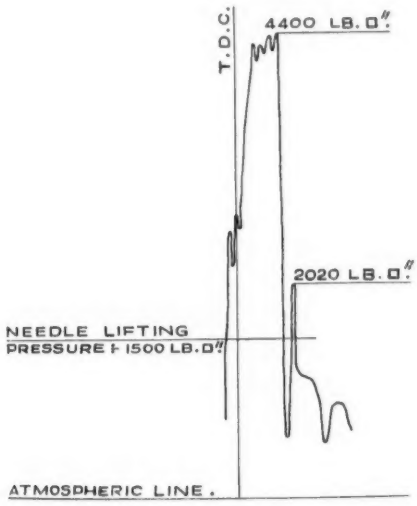
The apparatus used is shown in Fig. 4. The fuel pump was mounted on a casing containing a motor-driven camshaft, the cam having the profile chosen for the required injection system characteristics. The injection valve, with nozzle holes also designed for combination with the fuel pump and cam, was mounted in a cylinder of the same volume and shape as the proposed combustion chamber formed by the two pistons and cylinder liner, with the pistons on the inner dead centre. This cylinder was under a pressure representing the compression pressure. To maintain the required pressure conditions in the cylinder while the apparatus was working, a drain valve A and air-regulating valve B were used. At the time this experimental work was undertaken, the oscillograph, as now represented by the "Sunbury" and other instruments, had not been developed. A "Farnboro'" indicator was used to obtain the diagrams of pressure conditions in the delivery line. Diagrams were taken at points C, D, E and F, and showed that conditions were prejudicial to satisfactory working of the system. The experimental results agreed reasonably well with the preliminary analysis. The length of the piping necessary with the proposed system was plainly unsuitable. Further disadvantages were the undue pressure drop in the delivery line, and high residual line pressure due to the inability of any practical pressure-reducing device to increase sufficiently the line volume.

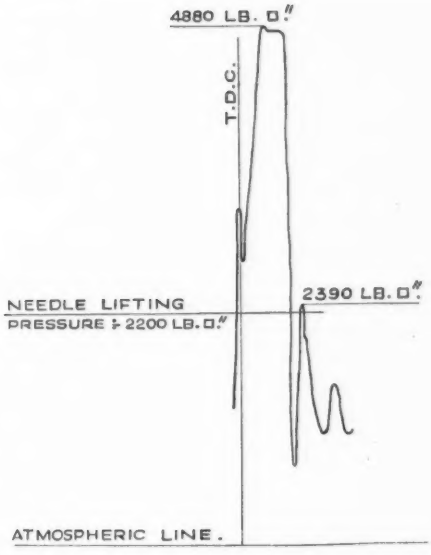
Ultimately it was decided to re-design the fuel injection system, placing the pumps as near as possible to each cylinder and to adopt two injection valves per cylinder. This arrangement is shown diagrammatically in Fig. 5.

Experiments similar to those described earlier were carried out, and Figs. 6 and 7 show the diagrams obtained.

Examination of Fig. 6 shows wave effect after the end of the main injection, with a peak pressure of 2,020 lb./sq. inch for a short period of time. This is above the lifting, or "blow-off" pressure (1,500 lb./sq. inch) of the nozzle valve setting. With these conditions a likelihood exists of secondary opening of the valve.

Fig. 7 shows results with conditions as for Fig. 6, but with "blow-off" pressure setting raised to 2,200 lb./sq. inch. The maximum injection





Figs. 6 & 7.—Fuel line diagrams taken with Farnboro' Indicator.

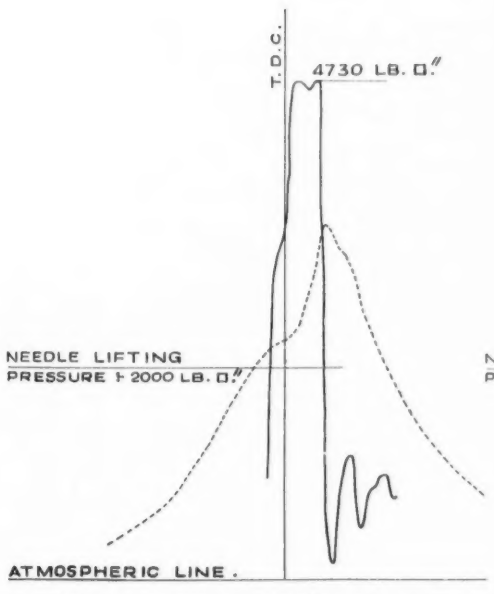


Fig. 8.—Fuel line and Cylinder pressure diagrams taken with Farnboro' Indicator.

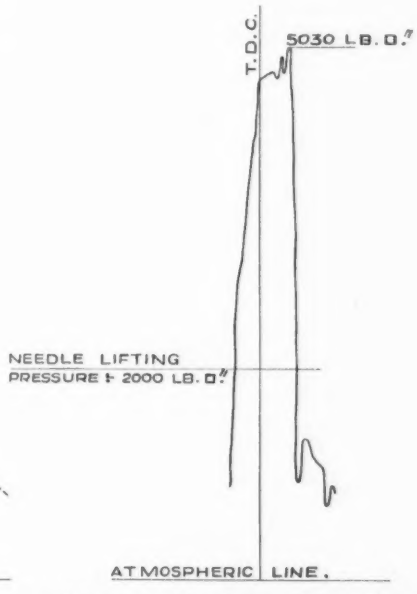


Fig. 9.—Fuel line diagrams taken with Farnboro' Indicator.

pressure rises from 4,400 to 4,880 lb./sq.inch, and the peak wave pressure, after injection, rises to 2,390 lb./sq. inch, i.e., only slightly above the lifting pressure. The valve needle, in these conditions, would not lift in the very short time available. This arrangement of equipment was adopted, and Figs. 8, 9 and 10 show diagrams obtained later on the actual engine.

In Fig. 8, the maximum pressure is 4,730 lb./sq. inch, which agrees closely with the figure obtained on the experimental apparatus. The pressure waves after injection are of small magnitude, this ensuring that no secondary opening of the nozzle valve occurs. At about top dead centre the rapid rise of pressure is checked momentarily. This is caused by the sudden increase in the volume of the system following on the lifting of the nozzle valve. The cylinder diagram is shown dotted. The " delay period " can be observed clearly.

Fig. 9 shows the pressure conditions at the fuel pump. Maximum pressure here is 5,030 lb./sq. inch. The difference between this pressure and the maximum pressure at the nozzle end of the system represents the frictional loss in the piping.

Comparison of Fig. 8 and Fig. 9 shows that a small but definite lag occurs between the production of a high pressure at the pump and the appearance of this pressure at the nozzle end of the system.

Fig. 10 was obtained under the same conditions as Fig. 8, except that a more viscous fuel was used. The maximum pressure is increased to 5,400 lb./sq. inch, and the effect of fuel of a different delay period is seen clearly in the dotted cylinder diagram.

Fig. 10a shows an actual record of pressure waves in the Fullagar injection system as finally adopted. The record was taken at the Company's Rugby Works by means of the Farnboro' electrical indicator fitted with a pressure reduction device. This record is referred to by Davies and Giffen in an I.A.E. paper, and by Heldt. The full line shows the variation of pressure at the pump end, and the dotted line that at the injection valve end. The pressure waves set up after the closing of the injection valve are very marked, but are not sufficient to cause the

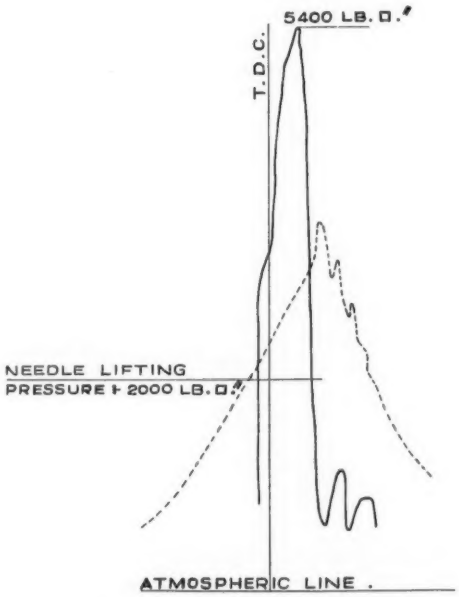


Fig. 10.—Fuel line and Cylinder pressure diagrams taken with Farnboro' Indicator.

valve to re-open—that is, there is no secondary injection.

It has been shown that the speed of propagation of the pressure wave is of the order of 4,400 ft./sec. In the case of the K-type engine, for example, where the length of the fuel delivery line is 1.66 ft., it takes

$$\frac{1.66}{4400} = 0.00038 \text{ sec.}$$

for the wave to travel from the fuel pump to the nozzle. As the engine runs at 600 r.p.m. and the maximum load injection period is approximately 20 degrees of crankshaft rotation, the injection period is

$$\frac{60 \times 20}{600 \times 360} = 0.0055 \text{ sec.}$$

It will be seen, therefore, that the pressure wave has time to travel approximately seven times through the line in both directions during the injection period.

In Fig. 10a, the pressure wave is seen to travel outwards and back only once during the injection period, the peak of the second wave as it arrives at the nozzle being below the opening pressure of

the nozzle valve. This is due to the fact that the delivery pipe line is 18 ft. long, or nearly eleven times the length of the line in the K-type engine.

The effect of the pressure waves in the pipe is to increase stepwise the pressure at the nozzle. The time interval between the arrival of successive steps depends essentially on the length of the line, while the amplitude of the waves depends on the initial velocity of the fuel in the line set up by the motion of the pump plunger. Viscous drag, or damping, decreases rapidly the amplitude of the wave.

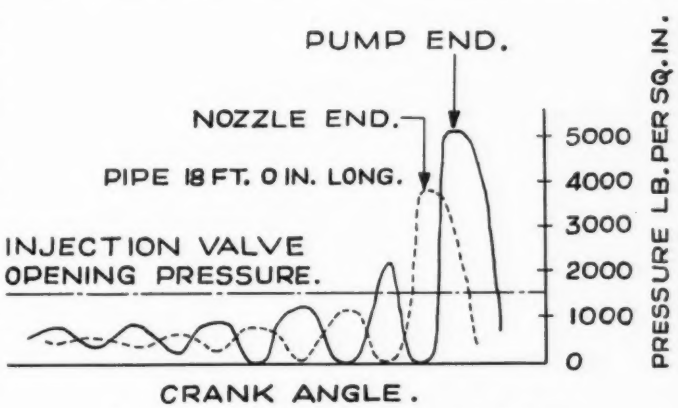


Fig. 10a.—Curves showing Pressure waves in Fuel Line.

Fig. 11 shows representative diagrams of the movement of a nozzle valve in the actual nozzle, as recorded by a cathode-ray oscillograph. The valve rises rapidly to the full extent allowed and then remains open for a length of time dictated by the load on the engine. When closing, the movement of the valve is rapid at first. The rate of closing during the last part of the movement, however, diminishes very much as the valve has to squeeze out the oil between the valve face and the seat. It will be seen that there is a delay corresponding to about 7 degrees of crankshaft rotation between full opening of the nozzle valve and beginning of combustion.

Penetration of Air Charge by Fuel Jets.

The distribution of the fuel mist throughout the air charge in the cylinders clearly plays an important part in the initiation of inflammation and the subsequent progress of combustion. Considerable research in this field has been carried out in Europe and America, and although it is known that in general the interaction between the motion of the fuel spray and the motion of the air charge is a matter largely of combustion chamber design, detailed study of the processes of injection operating in the cylinder show them to be inextricably mixed with those of ignition and combustion. In the case of the Fullagar engine the question of penetration was one of primary importance. The combustion chamber was roughly disc shaped, the vertical dimension between pistons at inner dead centre being small. With one injection valve, penetration would require to extend almost the diameter of the cylinder. In the case of the Q-size engine, this is 14 ins. ; in the R-size, 19 ins. These distances required pressures and time periods which were manifestly outside all practical considerations. It was therefore decided to adopt two injection valves arranged diametrically opposite across the

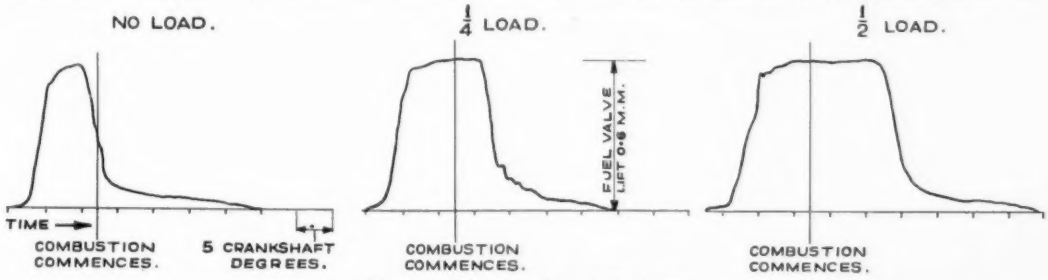


Fig. 11.—Diagram of Fuel Valve lift.

combustion chamber. This disposition of the valves halved the distance to be penetrated by any jet, and constituted a very great advantage in other directions.

The physical dimensions of the engine in consideration were such that the cost of unduly prolonged experimental running was certain to be great. The information available on the subject of fuel penetration was not considerable. Even at the present time the physicists and experimenters are not agreed as to fundamentals. Mehlig has advanced the theory that the ratio of the lengths of penetration in two given intervals of time is independent of back pressure ; that is, the compressed air charge in the combustion chamber. Sass has published tests which are claimed to show that the penetration is proportional to the square root of the nozzle hole diameter. Data obtained by Holfelder is quoted as supporting the claims of Mehlig. Schweitzer (America) has suggested that Mehlig's formulæ are incorrect, and claims that the experimental data of Beardsley and of Sass do not support Mehlig's theory.

Ten years before much of this information was available, it was necessary, in order to have some basis for the injection equipment design, to endeavour to obtain some information in regard to how the fuel jets might behave in the Fullagar engine cylinder. The only spray photography equipment in existence was that of the N.A.C.A., at Langley Field, Virginia, U.S.A. There, research on the subject of penetration had been carried to considerable lengths. As a result of the spray photography tests, it had been possible to calculate the velocity of the fuel spray at any instant, and it was found that the deceleration of the spray tip is closely represented by :—

$$-\frac{d^2 S}{d t^2} = -\frac{d V}{d t} = 2 K V^{1.5} \quad \ldots\ldots(1)$$

from which

$$S = \frac{V_0 t}{K V_0^{.5} t + 1} \quad \ldots\ldots(2)$$

where S = spray length or penetration in feet
t = time in seconds
K = a coefficient
V_0 = initial velocity in ft./sec.

The values of V_0 for various fuel pressures and a combustion chamber pressure were known, also corresponding penetrations for various values of t.

From (2)

$$K = \frac{V_0 t}{S \sqrt{V_0 t}} - \frac{1}{\sqrt{V_0 t}}$$

$$= \frac{\sqrt{V_0}}{S} - \frac{1}{\sqrt{V_0 t}} \quad \ldots\ldots(3)$$

Using the range of delivery line or nozzle pressures considered suitable for the equipment, penetrations of 5.2 inches to 8.2 inches were shown to be probable. With two diametrically opposed injection valves and a 14 in. bore cylinder these penetrations were very suitable. The higher figure showed that a lower maximum line pressure than originally anticipated could be used. It was, however, considered desirable to endeavour to check this out experimentally before any actual engine work was begun.

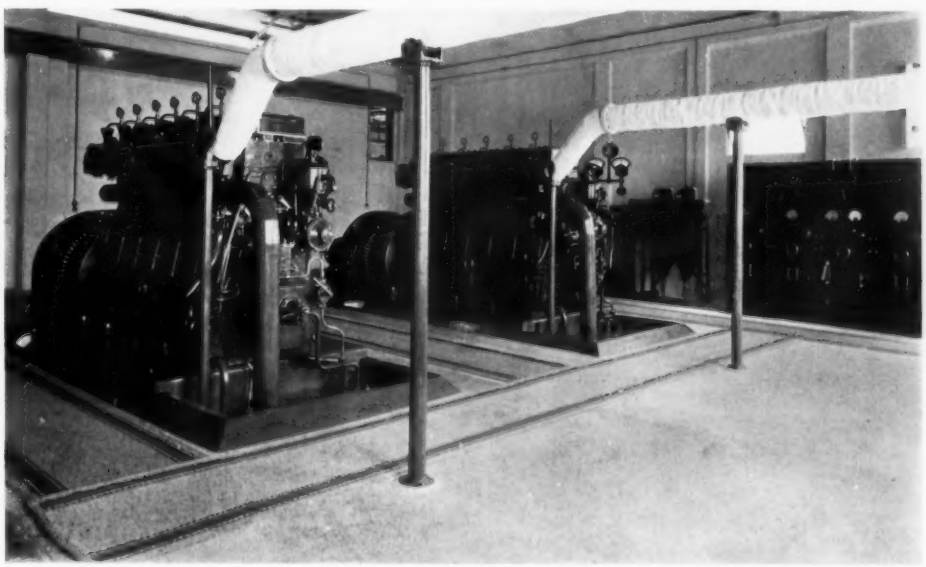
Bird (Cambridge University), in 1923, had made references to the use of water as a medium somewhat analogous to the cylinder compressed air charge. He had pointed out that the air into which injection usually occurs in a compression-ignition engine has 13 times the density of normal air, and since the kinematic viscosity $\left(\frac{\mu}{\rho}\right)$ will thereby be reduced to one-thirteenth of its normal value, injection into water will be practically equivalent to these conditions so long as viscosity is a leading factor in the motion. It was appreciated that, with injection into water, the temperature condition would be absent. This would affect appreciably the development of the spray, as vaporization proceeds from the surface of the oil droplets, so altering their state. Furthermore the kinematic viscosity of air increases considerably with temperature. The velocity of the droplets is reduced by the considerable resistance of the air charge, so that in the later stages the velocity may enter the zone of viscous motion.

Tentatively, it was considered that the matter resolved itself virtually into one dealing with the resistance encountered by a solid moving

through a fluid, analytical investigation of which is extremely difficult, especially as the "fluid" can be considered to be in a more or less turbulent condition. It was, however, decided to endeavour to make observations with injection into water. The apparatus substantially as shown in Fig. 4 was used, except that the cover was removed from the pressure cylinder G, and the cylinder filled with water. Arrangements were made whereby a very limited number of injections could be made, at the same time preserving the correct speed and pressure conditions. The first injection was seen in shape unexpectedly clear, with the extent of penetration well marked. It was possible to some extent to see the degree of diffusion which took place fairly close to the nozzle. In an extremely short time, however, the water took on the milky appearance applying to an emulsion, so much so that the experiment was not really of much value. A number of injections were observed by emptying the cylinder after each pair of injections and it was possible to confirm that the penetration of the fuel spray was substantially as expected from the calculations.

The injection equipment for the airless injection Fullagar engines as now built was developed in the way described and experience with some 70,000 B.H.P. has shown outstanding reliability and economy. Similar bases were used for the 4-stroke engines as represented by the K and L models. The fuel rates applying to these engines show a very high thermal efficiency. From 100 per cent. load down to 50 per cent. load, consumption curves show little variation. At the optimum point, figures of 0.35 lb./B.H.P. hour are obtained or a brake thermal efficiency of 39.9 per cent.

There would appear to be little prospect of much further improvement in the fuel economy of the modern compression-ignition oil engine. Advancement must, however, take place in the direction of the use of the heavier grades of fuels. The digestion of the present-day engine is a little sensitive, particularly in the case of the smaller higher speed designs. The organisation of the large oil companies is remarkable in the way they have catered, in various parts of the world, to the varying demands in the way of fuels, but the time must come sooner or later when most engines will have to operate satisfactorily on fuels which are now regarded generally as unsuitable.



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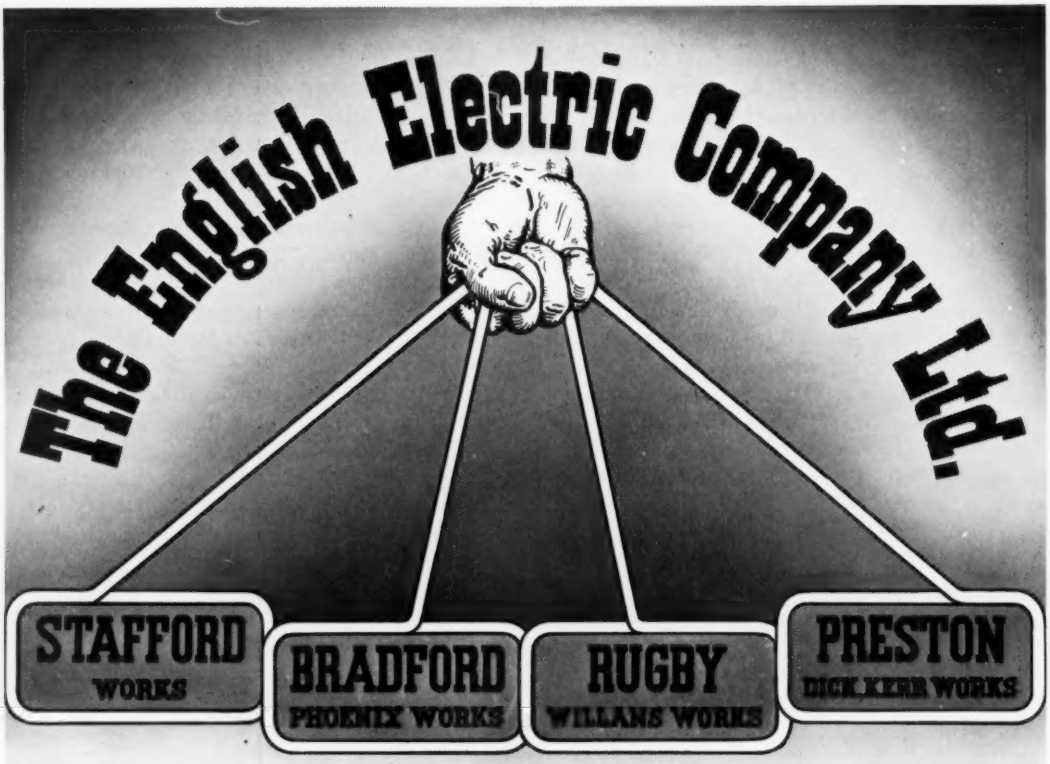

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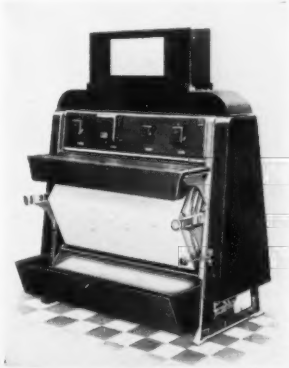

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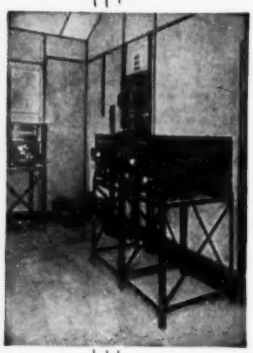

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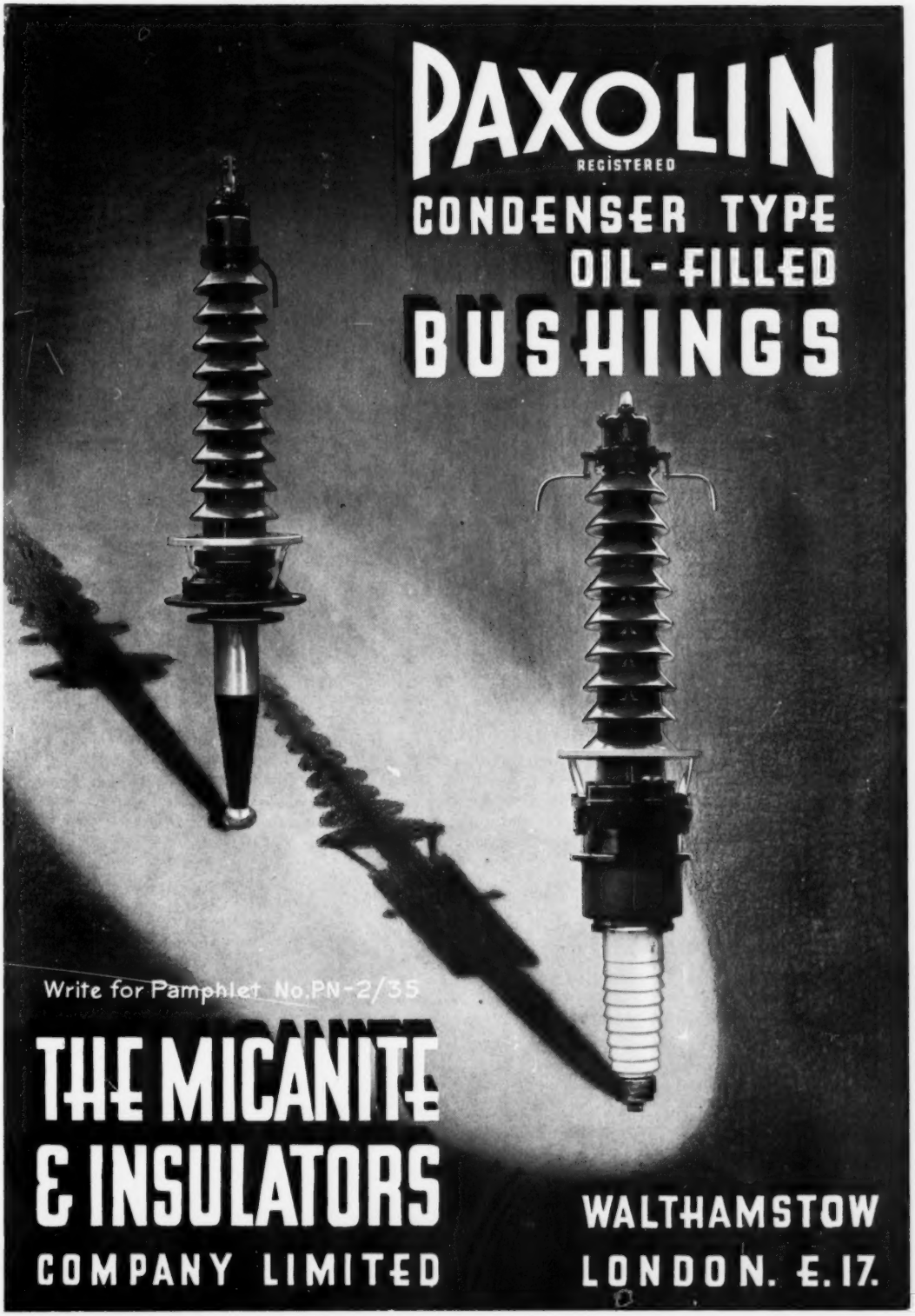
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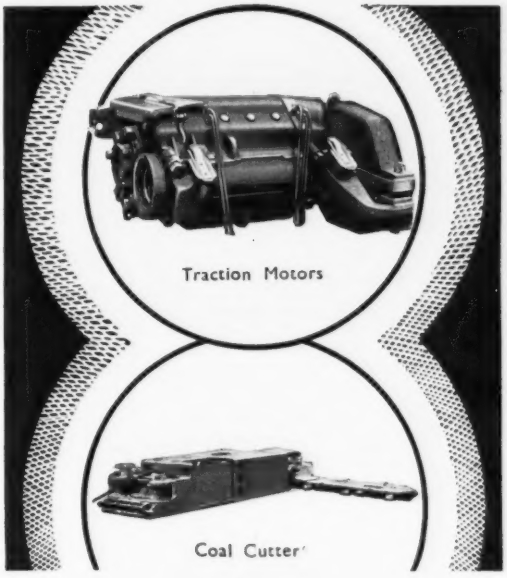

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